## THIRD DRAFT

# ON AQUATIC RESOURCES OF THE SAN FRANCISCO ESTUARY

NOT FOR CITATION OR DISTRIBUTION

BRUCE HERBOLD ALAN D.JASSBY PETER B. MOYLE

UNIVERSITY OF CALIFORNIA, DAVIS

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#### 1 Introduction

# 1.1 Physical Background of Sacramento-San Joaquin Estuary

# 1.1.1 Geologic setting

The Sacramento-San Joaquin Estuary is unlike any other river mouth in several significant ways. The estuary is the product of very recent geological activity. Orogenesis of the Coast Range blocked or diverted the flow of what had been a long series of independent coastal streams into a complex drainage with two main rivers flowing through the newly formed Central Valley (Atwater 1980). The resulting summation of the American, Cosumnes, Feather, Kern, Kings, McCloud, Merced, Mokelumne, Pit, Sacramento, San Joaquin, Tuolumne, Yuba, and other rivers produces the 25th largest outflow in North America from a drainage area that receives almost no rainfall for half of the year. The only escape for this outflow is a narrow notch in the Coast Range. Thus, the river channels must coalesce and narrow as they approach the sea, unlike most other deltas where channels split and spread over a broad flood plain.

Narrowing of the channels closest to San Francisco Bay and a highly seasonal pattern of outflow give the river tremendous hydraulic power so that its geological effects are disproportionate to its age. The river carved its way through low points in two series of hills and produced one of the most perfect natural harbors in the world. The three right angle bends which the outflowing water must negotiate on its way from the Delta through Carquinez Straits to the Golden Gate produced three large eddy pools, Suisun Bay, San Pablo Bay and South Bay. Local outflow in these areas (e.g. principally Denverton Creek into Suisun Bay, Petaluma and Napa Rivers into San Pablo Bay, and Alameda and Coyote Creeks into South Bay) played a much smaller role in shaping the topography of these areas, because they contribute less than 10% of the water entering the Bay. In this document "Bay" refers to Suisun, San Pablo and San Francisco bays, "lower Bay" refers to the Bay below Carquinez Straits, "Delta" refers to the Sacramento-San Joaquin Delta within the area encompassed by Antioch, Mossdale and Sacramento, and "Estuary" is used as the collective term.

The soil of most estuaries consists of deep layers of fine sediments carried from upstream. During the dry season sediments settled out in the Delta, although wind action is likely to have resuspended and redistributed them. Thus, the Delta acted as a large settling pool and islands developed as sediment-laden waters spread over higher ground, slowed down as they flowed among cattail and tules, and deposited their minerals along the edge. In this fashion the islands grew to resemble atolls. Growth of vegetation in the centers of these islands led to extensive development of peaty soils. In the wet season many sediments were transported all the way through the Delta and Bay to form large shoals in the Gulf of the Farallones. Within San Francisco Bay, mudflats are most abundant in the eddy-like portions of Suisun, San Pablo, South Bay. Central Bay contains much deeper areas than the other embayments (> 99 m) and has few shallow areas (Fig A.2). Because high outflows

periodically provide high flushing rates. Depths within the Bay range from large shallow areas where sediments have accumulated to quite deep areas that are subject to high current velocities (Josselyn 1977).

Glacial action brought layers of glacial sediments into the Delta so that soils interfinger deltaic sediments with layers of sand and gravel (Shelemon and Begg 1975). Burial and decomposition of large quantities of marsh vegetation yielded several areas where natural gas is abundant enough to be mined (Safanov 1962).

Tectonic movements have raised and lowered the passes through which river water must flow on its way to the sea. At times the notch in the Coastal Range has been as much as 40 m above sea level. Thus, for much of the recent history of the estuary, inland waters could only have flowed out for a short part of the year. The isolation of the Bay from the Delta has produced a sharply segmented estuary, with a Bay ecosystem dominated by marine taxa and a Delta dominated by freshwater forms. Most of the intensively studied estuaries of North America are on the Atlantic coast and they possess a long, shallow, braided channel where marine and freshwater influences interact. The Sacramento-San Joaquin estuary is similar to other estuaries of the Pacific Coast where most major rivers run into the ocean with limited areas of tidal marshes and other features typical of older estuarine systems.

## 1.1.2 Freshwater outflow, marine currents and hydrology

#### 1.1.2.1 Estuarine conditions

Picturing the estuary as a simple conflict of riverine vs. marine influences hides the complex interactions of hydrology, biology, and human influences. Although net water flow is from east to west, flow conditions change tidally, seasonally, and annually in response to oceanic conditions and to upstream rainfall patterns. Patterns of flow also differ among the four major embayments. Thus, the lack of a natural deep channel through South Bay gives it the characteristics of a lagoon estuary, while the entry of most freshwater into Suisun and San Pablo Bays give them the characteristics of a partially mixed estuary. San Pablo and Suisun Bay are components of a North Bay which is quite different from South Bay or the more oceanic Central Bay. Human activities alter flow velocities, volumes, and even direction in the sloughs and river channels of the Delta. Water management strategies in the Central Valley also affect hydrology and biology in San Francisco Bay.

The height of the Sierra Nevada usually leads to much of the precipitation falling as snow. This snowpack greatly moderates outflow from rivers of the Central Valley in comparison to coastal streams, such as the Russian or Eel rivers, where rainstorms are followed immediately by high outflow. Air temperature during storms affects the percentage of precipitation falling as rain or snow; warmer precipitation leads to greater immediate runoff and lower runoff later in the year. The Sierra snowpack reduces the suddenness of peak outflows and stretches the period of high outflow over several months. Nevertheless, prior to human intervention, outflow from the Delta usually fell to very low levels for

several months preceding the onset of the next wet season. The low-lying delta thus supported extensive wetlands, including ponds, sloughs, marshes, and a riparian strip along the rivers that was as much as 40 miles wide. Very low summer outflow permitted annual incursions of brackish water into the Delta.

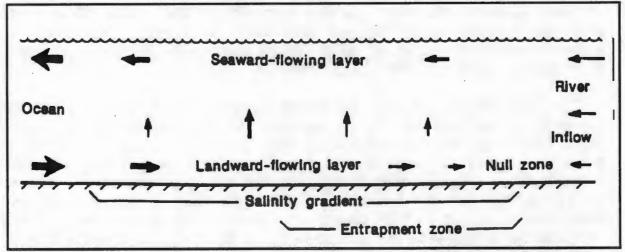


Figure 1 Hydraulic patterns producing the entrapment zone. Width of arrows indicates intensity of flow.

Outflowing fresh water produces several ecologically important conditions in San Francisco Bay. Sea water flows in to displace freshwater from the bottom. Thus, a bottom current of marine water often flows into the Bay while a lens of freshwater floats seaward on the surface. Either current, or both, may form eddies and deposit sediment in areas where topography causes the current to slow. Between the two currents is a plane of water exhibiting little net movement upstream or downstream. Mixing between the two currents increases as the bottom current proceeds upstream and at some point stratification breaks down (Figure 1). Landward flowing bottom currents receive a variety of sediments and planktonic organisms as the seaward flowing surface currents slow down. The breakdown of stratification reunites these sediments and plankton with the surface currents. Recycling of these sediments, with their advected nutrients, produce an area where planktonic algae accumulate and may benefit due to the high concentration of nutrients. Incorporation by algae, ingestion by animals or simple flocculation can all contribute to entrapment of riverine materials in this area. Prolonged residence times, due to the mixing of currents and the reinoculation of phytoplankton from downstream permits the build-up of high algal concentrations characteristic of this area. Similar mechanisms, augmented by behavioral traits, lead to concentration of zooplankton and fish in this area. A variety of names have been used to refer to this enriched area; we will refer to the plane of water separating the two currents as the "null zone" and the broadening of the null zone at the area where stratification breaks down as the "entrapment zone."

Generally, strengths of bottom currents mirror the strength of outflow. Under high outflow conditions bottom currents are stronger; low outflows of fresh water provide little stratification and bottom currents tend to be weak. Seasonal variation in tidal flows, and the consequent different volumes and velocities of the tidal prism, can greatly modify the effects of density-driven currents. With extremely high outflows, stratification occurs downstream of Carquinez Straits and the depth and volume of the downstream embayments prevents formation of a mixing zone. Within a broad middle range of outflows, bottom currents penetrate upstream into Suisun Bay or the lower river channels. Presence of the mixing zone in the extensive shallow regions of Suisun Bay increases the residence time of phytoplankton in areas of higher light. The resulting greater concentration of phytoplankton has often been cited as essential for planktonic fish larvae to survive (see Appendix A).

Flow patterns have become less variable in the Delta since the construction of dams on the tributary rivers. Seasonal water temperatures and salinities in the Delta have also become less variable as a consequence of the decreased seasonality of flow.

#### 1.1.2.2 Tidal flows

Tidal flows affect the primary productivity of the estuary and the productivity of its aquatic resources in many ways. On an average tidal cycle the volume of sea water entering the Bay, the tidal prism, is roughly equal to 24% of the volume of the Bay. The twice daily tidal cycle (mixed semi-diurnal) directly transports oceanic materials, nutrients and biota through the Golden Gate. In addition, the waters of the various subembayments are also moved through different habitats and between basins. The entrapment, consumption, or other use of these transported materials can produce a net flow of materials despite the cyclical movements of water. Thus, in the spring, water flowing out of the Bay on a receding tide may pick up nutrients from upwelling currents and bring them into the Bay on its return. Contrarily, tidally transported water from the Bay in the winter may be replaced with nutrient-poor water. At the other end of the estuary, tidal currents can regularly move planktonic animals within range of entrainment by various diversions in the Delta. The magnitude, or even the net direction, of any such transports is largely unknown.

Transport between embayments and the important effects of tidal transport of water through marshes and other habitats will be discussed below in terms of the movement of fixed carbon. The main pattern of importance to animals is that, due to the deep channel connecting Central, San Pablo, Suisun Bay, and the Delta, a greater volume of water is moved by tidal action through the Northern Bay than through South Bay. Corollary to this is that the South Bay has the largest amount of tidal mudflats (Nichols and Pamatmat 1988). Primary productivity of the South Bay tidal mudflats is increased because more of the spring low tides occur during daylight hours so that the benthic algae receive the maximum insolation during their principal period of growth (Nichols and Pamatmat 1988). In other parts of the estuary tidal actions interact with other environmental variables to produce synergistic effects that are difficult to anticipate from consideration of one factor at a time.

Tides directly affect aquatic animals in two main ways. The twice daily influx of ocean water subjects stationary animals to a strongly varying salinity regime in most of the Bay. This effect is strongest in Suisun Bay where freshwater presents an entirely different osmotic problem than brackish water. The changing salinity of Suisun Bay is thought to have been a major factor in preventing the development of a large benthic fauna there (Nichols and Pamatmat 1988). This idea developed from observing the invasion by large numbers of the clam *Mya arenaria* when the water remained salty during the drought in 1976-77 and their rapid disappearance upon the return of normal river flow (Nichols 1985). The idea has received additional support by the recent invasion and rapid population growth of the euryhaline clam *Potamocorbula amurensis*.

The effects of tides on aquatic resources are also strongly influenced by the behavior of tidally transported animals. For example, by sinking to the bottom for part of the tidal cycle and swimming into the water column during the other part, even small animals can migrate long distances. Since tidal flows approach 3 ms<sup>-1</sup> such migrations can proceed quickly. The presence of a tidal cycle every twelve hours also permits benthic animals, particularly shrimp, to combine their use of tides for migration with a need to minimize predation by being out of the substrate only during the night (Siegfreid et al. 1978).

#### 1.1.2.3 Winds

Winds play an important role in resuspending bottom accumulations of nutrients, organic material, and organisms, particularly the larger species of phytoplankton. The effectiveness of winds in disrupting stratification and in reinjecting bottom material into the water column is a function of the topography of the embayments, and the strength and direction of the winds. In the deep water channels and in most of Central Bay, the water is too deep to permit much mixing, whereas the shoals of South Bay, Suisun Bay and San Pablo Bay can often be thoroughly mixed. Winds in the Bay area are seasonal with strong westerly or north-westerly winds in the summer (Conomos et al. 1985).

Large shallow areas and strong winds provide a thorough oxygenation of most Bay waters (Hartman and Hammond 1985). Unlike most other estuaries, the oxygen concentration profiles in the Bay show saturation with oxygen all the way to the soil-water interface. Until the 1960s, this thorough mixing was often overwhelmed by the high biological oxygen demand of water discharged into the Bay in crudely treated waste water. The lower rates of water exchange of South Bay with the ocean or with other embayments led to pronounced problems of low oxygen concentrations available to benthic organisms (Skinner 1962).

# 1.1.2.4 Oceanic processes

The northwest to southeast slant of the California coastline is interrupted by the outthrust of Point Conception. Generally, the coast below Point Conception is under the influence of the northward flowing Davidson Current which brings subtropical waters northward. At

Point Conception these waters meet the southward flowing California Current which carries subarctic waters. These very different currents produce profound differences in the biological communities they support with, for instance, tropical fish families populating kelp forests off southern California whereas similar kelp forests in northern California are occupied by temperate zone families (Foster and Schiel 1985). Near San Francisco Bay, the oceanic conditions respond markedly to the shifting strengths of the Davidson and California Currents and the coastal zooplankton populations fluctuate in response (Hatfield 1983).

Oceanic conditions vary in most years through three seasonal stages: the upwelling period, the oceanic period and the Davidson Current period (Skogsberg 1936; Bolin and Abbott 1963; Wild and Tasto 1983). El Niño events are usually associated with the failure of this seasonal progression. The most significant ecological impact is associated with the strength of the upwelling period from March through August. At this time, strong northwesterly winds and southerly surface currents produce offshore Ekman transport of nutrient-poor surface waters and their replacement along the coast by nutrient-rich bottom water. The strength of the upwelling is closely tied to the abundance and species composition of the near-shore zooplankton community (Peterson 1973; Peterson and Miller 1975; Peterson et al. 1979; Hatfield 1983). The oceanic period marks a shift in climatic conditions, there is a lull in winds and 8 water flow in September and October. In November, southerly winds and the north-flowing Davidson Current produce a downdraft of surface waters along the coast. The vertical movement of water causes surface temperatures to decline during upwelling and causes deeper water temperatures to rise during the late fall and winter. Upwelling is strongest near San Francisco Bay during June and July (Bakun 1975).

Year to year changes in oceanic conditions are a result of large-scale meteorological activity. The most striking recent fluctuation occurred during *El Niño* conditions of 1983. Warmer tropical waters at the surface produced density differences between surface and bottom waters which were too strong to be broken down by Ekman transport. Consequently there was little upwelling, and productivity at all trophic levels was reduced. Upwelling may also be important in reinforcing the circulation of bottom currents into the bay, whereas Ekman transport of surface waters promote onshore movement of surface waters and reduce estuarine circulation (Peterson et al. 1989). Pacific herring was one species whose decline under *El Niño* conditions of 1976-1977 and 1983 was well documented. These conditions in 1983 were accompanied by massive storm systems and record-setting precipitation of rain and snow. The resulting high outflows led to water residence times that were very short and productivity was very low. In addition, the mixing zone was far downstream of its normal position. Thus, low oceanic productivity lowered the marine contribution of productivity to the estuary at the same time that riverine production was small and hydrodynamic processes failed to produce the usual accumulation of fixed carbon.

Year to year variations in oceanic conditions, particularly upwelling, are thought to control recruitment success in a number of marine species. However, there does not appear

to be any periodicity to the strength of upwelling while there is obvious periodicity in populations of Dungeness crab, coho salmon or chinook salmon (Botsford et al. 1982).

Multi-year changes in oceanic conditions have also been recorded with corresponding changes in the abundance of aquatic resources. In the years following 1957 mean ocean water temperature and mean sea level rose in response to the greater influence of subtropical ocean waters and stronger southwesterly winds (Huang 1972; Namias and Huang 1972). Not surprisingly, these conditions particularly strengthened the conditions associated with the Davidson Current (Sette and Isaacs 1960). Dungeness crab is one species that apparently responded to this general change in conditions (Wild et al. 1983).

# 2 Major Factors Affecting Aquatic Resources

#### 2.1 Introduction

Under natural conditions, the Estuary was a highly variable system. The seasonal patterns of freshwater inflow were predictable in general timing. High inflows followed snow melt from the Sierras in the spring and dropped to a low point in autumn. However, the amount of freshwater inflow and its exact timing within the spring season was enormously variable. Likewise, the occurrence of high tides in spring and fall is a highly predictable occurrence but the extent to which the tides push salt water into the estuary depends on both the amount of outflow and the strength of the winds blowing at the time. While this natural variability has been dampened somewhat through human control of freshwater inflow, other human impacts on the estuary have made the estuary an increasingly difficult place for large populations of most organisms to persist. The most severe changes were the result of the combined effects of agricultural development, hydraulic mining, and the introduction of exotic species, although other factors, such as urban development and exploitation of some species played a role as well. In the following sections we discuss in general terms the effects of (1) natural variability in freshwater inflow, (2) water development, (3) pollution, (4) diking and dredging, (6) mining and siltation, (7) introduction of aquatic organisms, and (8) exploitation.

#### 2.2 Natural variation in outflow

The most commonly cited control on abundance, distribution, and reproductive success for many species of fish in the Sacramento-San Joaquin estuary is the quantity of river flow through the Estuary (Goldman 1970; Turner and Chadwick 1972; Peterson et al. 1975; Chadwick, et al. 1979; Conomos 1979; Rumboltz 1979; Kjelson et al. 1980; Herrgesell et al. 1983; Stevens and Miller 1983). Flow affects aquatic resources in myriad ways. Some species spawn most successfully on flooded vegetation, which is more available in years of high outflow (Daniels and Moyle 1983). Recruitment of some anadromous species is much higher when high outflows provide access to additional spawning habitat. Many anadromous species and marine species that spawn in the Bay require a sufficient plume of freshwater to allow them to find their way into the Golden Gate. River water carries nutrients into the

estuary and low nutrient loading may, at times, limit autochthonous production (Ball 1989). River water increases its load of phytoplankton as it approaches and passes through the Delta (Greenberg 1964). The importance of such allochthonous production for Bay ecosystems is unknown, but possibly great (Appendix A). Outflow controls the bottom marine currents carrying many young ocean-spawned fish and invertebrates into the Bay. The interaction of outflow with marine currents controls whether the mixing zone is located in the shallow topography of Suisun Bay or in the deeper channel areas upstream or downstream.

The volume of water flowing into the Delta is extremely variable across years (Figure 2). Years close to the average are less common than those much wetter or drier. The last 15 years have encompassed the wettest year on record (1983) and the wettest month on record (February 1986). Two of the longest and driest droughts on record also fell in this period (1976-1977 and 1985-present). During the drought year of 1990 the Central Valley also experienced the wettest May on record. There is no appreciable autocorrelation of outflow in one year with outflow in the preceding year (r=.10). However, within a year, outflow from month to month is strongly autocorrelated (r=.68), so a year of high outflow typically has high outflows across several months; wet months during dry years, like February 1986 and May 1990, are exceptional.

Studies of the fishes of the Sacramento-San Joaquin estuary have focussed on identifying those species characteristic of different outflow conditions. Stevens and Miller (1983) identified high outflows as supporting higher populations of American shad, longfin smelt, and chinook salmon. Armor and Herrgesell (1983, 1987) identified several abundant species as characteristic of wet years or dry years. Pearson (1989), for several species in the South Bay, differed with the findings of Armor and Herrgesell.

The possible mechanisms by which flow variability, either in the rivers or in the estuary, could control fish recruitment were summarized in Stevens and Miller (1983):

- 1. Low flows during incubation following high flows during spawning often results in dewatering of salmonid redds, causing mortality of eggs, embryos, and alevins of salmon. Many other fishes spawn around submerged objects and their adhesive eggs would then be subject to the same sort of mortality during years with sharp differences in outflow across a short time span.
- 2. Low flows expose a higher proportion of fish populations to possible entrainment by water diversions. A higher proportion of water is taken in years of low inflow, and greater numbers of fish are entrained.
- 3. Smaller river volumes increase the density of young fish in the river channels, thus permitting more efficient foraging by predators.
- 4. Moderately high flows increase the diversity of habitats available, especially increasing the availability of shallow habitats where young fish enjoy greatly reduced predation pressures.
- 5. Moderately high spring/summer flows increase zooplankton abundance in the Bay, resulting in more food available for larval striped bass and smelt.

The multiple effects of outflow on aquatic resources is mirrored in the adaptations of many native species. The dominant fishes in the Sacramento-San Joaquin Delta are minnows (Cyprinidae). California's minnows are exceptionally large as a result of their ability to postpone breeding in dry years. The energy saved by not breeding is put into growth so that older fish can be quite large (>1 m) and, because fecundity is size dependent, very fecund in years of high outflow. Large size also probably permitted widespread movements of individuals so that streams dewatered in dry years could be rapidly recolonized by downstream populations. The two small native cyprinid fishes (speckled dace, Rhinichthys osculus, and California roach, Lavinia symmetricus) are not found in the estuary. Splittail are one of the most euryhaline minnows, reflecting the formerly frequent intrusion of salt water into the Delta.

Recent changes in outflow that have had obvious impacts on aquatic resources are the severe drought of 1976-1977, the dry year of 1981, the record setting wet year of 1983 (accompanied by dramatic changes in oceanic conditions), the drought of 1985 to the present which was interrupted by the wettest month on record in February of 1986. Although global warming is popularly supposed to be revealed in the increasing frequency of drought conditions, tree ring studies have shown that California has had numerous periods of extended drought. Recent conditions may simply reflect the generally episodic nature of California's climate; a mean outflow can be calculated but few years are close to the mean and outflow usually changes greatly from year to year.

# 2.3 Water development

Rerouting of water within the Central Valley was one of the first impacts of early agriculture and mining. Lakes that used to form in low areas of the San Joaquin Valley were drained and their beds were diked and farmed. Within the Delta the direction of water flow in channels changes in response to diversion practices. Secondary impacts of water diversion on aquatic resources include: entrainment of all life stages, transport of species into new areas, changes in the distribution of temperature and conductivity isolines, alteration or confusion of migration patterns of spawning adults or outmigrating young, and entrainment of organic carbon sources for the food web.

Although construction of diversion facilities are separate historical events, the effects of diversion are one of the few linear trends apparent in the hydrologic features of California. In examining the correlations within the records of river flow, export rates, precipitation, etc., (contained in the DAYFLOW program of the State Department of Water Resources) the variability across years can be divided into two main principal components. Flows in each of the rivers, precipitation and total delta outflow covary as a unit and account for more than 90% of the measured variability. The association of export rates with increasing year constitute the second principal component and account for most of the remaining variance. The tight correlation of export volume with year makes it difficult to separate the effects of diversion from other linear changes, such as increasing urbanization, that may account for a portion of the observed changes in fish abundance through time. To address this problem we

suggest effects of diversion that may be responsible and then examine different species or different areas to attempt to corroborate the proposed mechanism.

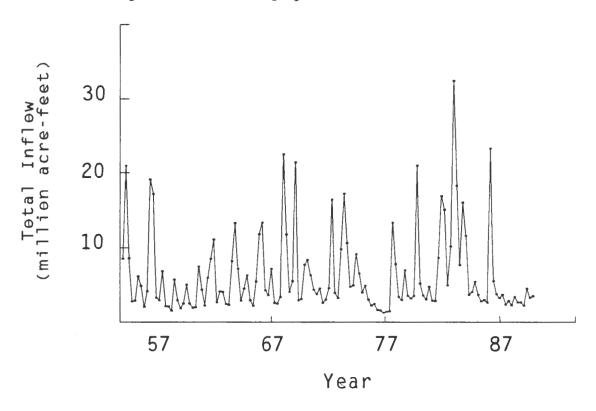


Figure 2 Quarterly inflows (in millions of acre-feet) into the estuary, estimated by the DAYFLOW model.

Diversion of inflowing water can alter all the cited effects of outflow. Water is retained and diverted by numerous channels and reservoirs on tributaries to the estuary and these diversions account for about 30% of what is calculated to be the Delta's mean annual unimpaired flow. Agricultural diversions within the Delta claim about 1 million acre-feet of Delta inflow. These agricultural diversions are largely unscreened and are probably a major cause of larval and juvenile fish mortality. The greatest recent change in hydrodynamics of the Delta is associated with diversion of water from the Delta. The rate of these diversions has been increasing rapidly over the last 20 years and now takes as much as 60% of the inflowing water (Figure 3). The State Water Project and the federal Central Valley Project together comprise one of the largest water diversion projects in the world. In addition to simply altering the effective outflow downstream, diversion can alter the direction of net flow; opening of the cross-delta channel transports water of the Sacramento River through the lower reaches of the Mokelumne to supply the state and federal water projects. Low outflow, when combined with high rates of diversion results in a net movement of Sacramento River water and water from Suisun Bay up the lower San Joaquin River

channels. Diversions have intensified and broadened their impacts on flows within the Delta in the last few years. In water year 1987-1988 more water was exported than flowed into the Bay. This export of water from the Delta has been the largest change in water use patterns over the last 20 years and has coincided with declines of fish abundance. One purpose of this study is to identify which species appear most sensitive to the myriad impacts of diversion.

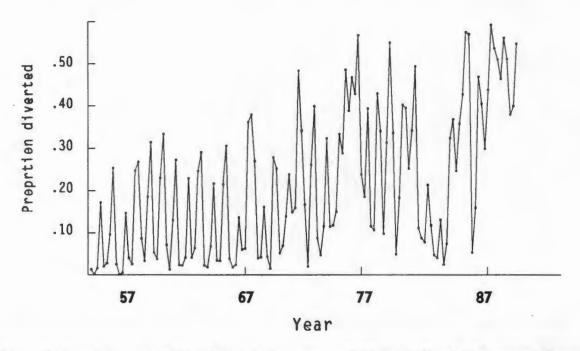


Figure 3 Quarterly proportion of delta inflow exported by State Water Project and Central Valley Project Pumps, from the DAYFLOW model.

Long term trends in outflow have been the subject of several analyses and vigorous debate. The amount of freshwater entering the Bay is 50 to 60 percent less than expected in the absence of upstream development and delta diversions (Meyer and Davoren 1981; Nichols et al. 1986; Rozengurt et al. 1987). Operation of diversions and upstream dams have smoothed the annual pattern of outflow so that the summer and fall flows are much higher than formerly.

A period of very low precipitation in the earliest years recorded (1921-1935) and a shift toward precipitation falling as rain rather than snow results in an increasing trend in delta inflow over the period of record (Fox et al. 1990; pers. comm. F. Nichols USGS). At the other extreme San Francisco Bay has been compared with the Sea of Azov which has received almost no freshwater inflow in recent years and has lost a third of its surface area.

Most analyses of freshwater inflow to San Francisco Bay have concentrated on the period since the large-scale diversions became active. The setting of annual entitlements of water to contractors by the state, despite the intrinsic high variability in the amount of water available in a given year, has resulted in an amplification of frequency and degree of drought conditions in the Bay (Rozengurt et al. 1987). The annual fluctuations may not be entirely unpredictable; between 1921 and 1978 inflowing water to the Delta shows evidence of 14 year cycles which have been found for other large drainages (Rozengurt et al. 1987). Proposed increases in water diversion in the future will continue to have their greatest effect on spring outflows, when several species of fish are migrating into the Delta and Bay. Currently mean annual spring diversion rates are around 60% and can be expected to rise to approximately 86% in future dry years. Average annual reductions in outflow can be expected to rise from 48 to 59%, and the modification of outflow can be expected to decrease the frequency of flushing flows (Williams and Fishbain 1987). These high diversion rates do not simply intensify the effects of normal droughts, but they produce extended periods of anomalous flow patterns in the Delta.

Long term records of precipitation in California from the analysis of tree rings show that the 20th century has been a period of exceptionally high rainfall compared to the three preceding centuries (Figure 4; Fritts and Gordon 1980). There seems to be no reason not to expect a return to the earlier rainfall patterns.

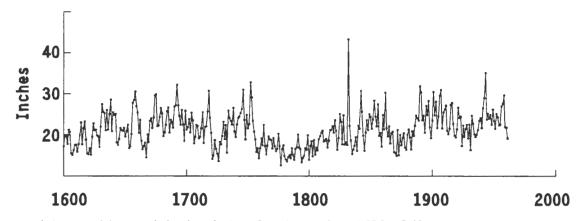


Figure 4 State-wide precipitation index for the period 1600-1960 based on analyses of tree rings.

Rather than contribute further to the hotly debated future of water projects in California we attempt to examine the likely effects of present water projects on aquatic resources. Water diversion takes very small proportions of Delta inflow in wetter years and the recent high proportions are a result of a long drought period during a time of high diversion rates. The simple exacerbation of drought effects by water diversions and the changes in net flow direction, which can only be caused by diversions, are a principal point of interest in

examining the trends in abundance for fishes of the estuary. However, consistent year-round data on fish abundances are only available for the last 10 years so it is difficult to assess how the populations may have behaved in earlier drought years.

#### 2.4 Pollutants

Changes in pollutant loads into the system will affect species in relation to three characteristics: the degree to which they are exposed to pollutants, their sensitivity to a given pollutant, and their trophic patterns in regard to bioaccumulation of pollutants. The future of pollution in San Francisco Bay is the subject of another Status and Trends Report and will not be addressed in depth here. The major pollutants affecting aquatic resources in the Bay are petroleum based, including polychlorinated biphenyls. Fish in aquaria are used to monitor the effects of outflows from refineries etc., but little work has been done to assess the impact of such pollutants on free-ranging populations in the Bay. PCBs have been shown to be at high levels in starry flounder collected from San Pablo and Central Bays and these fish show decreased reproductive abilities (Spies et al. 1988; Spies et al. 1990). It is difficult to determine the contribution of pollution load to the decline of this population (see section on starry flounder).

Other sorts of pollution in the Bay that particularly affect aquatic resources include thermal plumes, primarily those from the PG&E plants in Suisun Bay and in South Bay. Thermal plumes affect aquatic resources in a variety of ways. The warm water provides a temporary refuge for threadfin shad washed down from the Delta at the start of the wet season while, on the other hand, warmer water can be an additional stress on fishes returned to the Bay from the fish recovery operations at Tracy. The restricted geographical range of thermal pollution limits its effect on aquatic resources, but the location of the outfalls into regions used for spawning by smelt and herring have the potential of affecting those species disproportionately. Some species are apparently drawn to the warmer waters nearer thermal outlets and may suffer disproportionately when those outlets fluctuate.

Principal pollutants in the Delta are the agricultural chemicals and their derivatives that are heavily used throughout the Central Valley. Recent concerns for humans of pollutants in Delta waters have centered on the concentrations of trihalomethanes (THMs) in Delta waterways, but the effects on aquatic resources of such carcinogens is unlikely to be a major problem. The switch to short-stem rice by Sacramento Valley rice farmers was accompanied by increased use of pesticides and runoff from these waters may contribute to reproductive difficulties of striped bass (see section on striped bass).

# 2.5 Waterway modification

The earliest, and probably most profound, cause of change in aquatic habitat in the estuary was the introduction of European methods of agriculture into the Central Valley. Diking the rivers and clearing riparian vegetation began to change the lower parts of the valley from seasonal freshwater marsh to dry cropland. California has few natural lakes, and

the two Delta species that were probably most lacustrine in their habits are the two that are now extinct: thicktail chub and Sacramento perch. Populations of Sacramento perch remain in isolated lakes outside their native range. Populations of the genus *Gila*, to which the chub belongs, show much evidence of morphological specialization to local conditions (Moyle 1976). Characteristics of the thicktail chub include a number of features indicative of life in still water. Both species were formerly very abundant; Sacramento perch and thicktail chub are among the most abundant fish remains in Patwin Indian middens (Schulz and Simons 1973) and Sacramento perch were commercially harvested in the early days of San Francisco.

# 2.5.1 **Diking**

Diking of islands in the Delta began on Merritt Island in 1852. Dikes were constructed of dredged materials from the river or from the interior of the island. The dikes consisted of fine river sediments, easily degraded peaty soils, or a combination of both. Such diking led to weak dikes, depressed island interiors, and deeper, more U-shaped channels in the river. Water flows more quickly in dredged channels and the vertical walls are easily eroded. Early efforts to bolster the dikes relied on simply widening them so that erosion took longer.

A secondary effect of diking was to change river habitats and primary productivity. Restriction of water to channels increased water velocity and lead to decreased residence times of water in the estuary and less time for phytoplankton to grow. The transformation of vast areas of freshwater marsh into cropland effectively eliminated the contribution of marsh productivity to downstream food chains. Approximately 10% of the Delta is now aquatic habitat and 70% of that is deep, open water habitat (USACE 1979) leaving less than 3% in a state similar to the majority of the Delta habitat 150 years ago. Channelization removed the shallow margins of most river channels and prevented the growth of benthic algae. Before diking, diversions, and dredging began, long residence times may have limited productivity within the Delta. During low flow, summertime conditions high concentrations of phytoplankton may have blocked light penetration to most of the water column with a consequent decline in productivity. Shortened residence times appear likely to have reduced productivity within the Delta for most of the period of development, but an accurate model of productivity processes within the Delta has yet to be developed.

Diking has exerted a growing impact on the Delta since 1852. Reinforcing levee banks with rock revetments ("rip-rapping") and bringing publicly owned levees into conformance with federal guidelines of the US Army Corps of Engineers has greatly reduced the incidence of levee failure. Only two inundated islands are today unreclaimed - Big Break on Sherman Island in the western Delta, and Frank's Tract (formerly Mildred Island) in the central Delta. Due to subsidence, soil oxidation, and loss of soil by plowing and exportation, the central portions of many islands are 20' or more below the level of the surrounding water. Thus, inundation would not restore the lost shallow habitats. Intentional inundation for temporary water storage provides a possible use for these islands that would greatly reduce their rate of subsidence and would reduce the problem of levee maintenance (Jones and Stokes 1990).

Diking and agriculture affected surviving fish species of the Delta in several ways. The following description of effects relies on the reproductive and trophic studies summarized in Wang (1986) and Moyle (1976). Sacramento splittail, Sacramento blackfish, and perhaps longfin and Delta smelt, require submerged vegetation for spawning and the removal of marshlands removed most of their potential spawning habitat. Prickly sculpin lay their eggs in chambers among the roots of emergent vegetation and they similarly suffered a decline in spawning habitat. Young fishes of all species suffered a massive reduction in the shallow habitats most of them use to escape predation. Tule perch, as consumers of the invertebrates living on emergent vegetation, lost much of their foraging area. Splittail today can be found foraging, as well as spawning, in shallow, flooded areas (Moyle 1976) and it seems likely that they would have formerly used the island interiors.

# 2.5.2 Dredging

The first dikes were built from dredge spoils. Dredging activities gained momentum from the flooding that resulted from upstream hydraulic mining. Deep water ship channels were dredged so that inland cities could engage in port commerce; Stockton today still celebrates its status as the easternmost port in Northern California in its nickname of 'The Sunrise Port.' Dredging and dike building in the Delta changed the character of the habitat and doubtless caused major, but undocumented, shifts in the manner in which fishes used the delta.

Direct effects of dredging on aquatic resources today are greatly reduced by the restricted number of sites at which dredged materials may be deposited and regulation of quantity and timing when spoils may be dumped. Direct entrainment by dredge operations does not seem to be an important effect on anadromous fishes (Larson and Mohle 1990; McGraw and Armstrong 1990). Dredge spoils have not been found at levels sufficient to cause death of fish (Segar 1990). Any limiting effect on fishing success would probably be due to either decreased feeding by fish so that they take bait less often or by temporary migration away from Central Bay when dredging discharge rates are high. Available data are inadequate for analysis.

The most significant impact of dredging on aquatic resources appears to be the resuspension and release of sediments and pollutants into the water column. However, separating the effects of original contaminations from resuspensions requires considerable more background information on the effects of pollutants on the aquatic life of the Bay then has been gathered to date. The plume from dredge disposal at Alcatraz does not persist for long, but it is likely that much of the plume remains suspended and is moved away from the dump site by tides (Segar 1990). Because finer sediments stay suspended longer and show higher toxic contamination, even though turbidity itself may not be at levels sufficient to harm fish, there is danger of toxic effects on fish (Segar 1990).

The effects of dredging and dredge disposal are expected to lessen in the near future (Hanson and Walton 1990). The San Francisco Bay Regional Water Quality Control Board has called for a ban on aquatic disposal of dredged material from all new projects in the bay and has established limits on the amount of material from maintenance dredging permitted at each disposal site. Finally, the board required that dredging activities be restricted in area and time to minimize effects on other beneficial uses of San Francisco Bay; specifically addressed were the needs of Pacific herring, striped bass, and king salmon.

# 2.6 Mining and siltation

Almost concurrent with the first diking of Delta islands was the advent of hydraulic gold mining in the Sierras. After the 1847 discovery of gold near a tributary of the American River, mining rapidly progressed from simple panning or sluice boxes in the stream to the use of high pressure hoses and large bore water cannons to wash down much of the hillside. Miners constructed elaborate water systems to feed their operations and, in the 1880's, hydraulic mining rerouted and used approximately 740 million cubic meters of water each year (Hagwood 1976). By way of comparison, average delta inflow is approximately 18 billion cubic meters and the current water diversions export about 6 billion cubic meters.

The main impact of hydraulic mining on downstream sites was the introduction and transport of large quantities of silt. Siltation of river channels raised the bottom of the Sacramento River by 6 m and led to extensive flooding of the rapidly growing city of Sacramento. Of the 1.15 billion cubic meters of extra sediment estimated to have been brought into the Sacramento-San Joaquin estuary 155 million are estimated to have settled in Suisun Bay, 436 million in San Pablo Bay, and 249 million in South and Central Bays; these volumes translate to new layers of sediment measuring 1 m in Suisun Bay, 0.8 m in San Pablo Bay and 0.2 m in South and Central Bays (Gilbert 1917). Hydraulic mining was banned in 1884 but the silt added to tributaries may have continued to affect water quality in the estuary until as late as the 1980's (D. Ball USBR, pers. comm.).

The effects of mining on the aquatic resources of the estuary were undocumented but undoubtedly devastating. Siltation and dewatering of spawning streams must have particularly reduced salmonid recruitment.

#### 2.7 Introduction of species

Most changes in the estuary have been sudden changes of state rather than linear trends across years. For aquatic resources this has been most noticeable through the introduction of non-native species. Populations of introduced species have either mushroomed or collapsed. As with most introduced species (Herbold and Moyle 1986), successful introductions into the Sacramento-San Joaquin estuary often have followed major changes in the physical structure of the rivers and estuary by humans. The siltation of the rivers by hydraulic mining and the consequent success of striped bass and American shad typify this process. The failure of several early attempts to introduce channel catfish and their sudden explosion after Shasta

Dam stabilized salinity and provided more consistent year-round flows in the rivers and the Delta provides another example (Herbold and Moyle 1989). Although the particular habitat change responsible that permitted the establishment of a particular exotic species into the Delta can only be the subject of speculation, the general observation that introduced species almost always follow habitat alteration appears to be as true in the Estuary as it is for the rest of the world (Elton 1958; Herbold and Moyle 1986; Fox and Fox 1986).

Justifications for introducing species frequently refer to 'vacant niches' in the environment, but this idea can be refuted either logically (most ecological definitions of 'niche' cannot be used in any 'vacant' sense) or through experience gained of hundreds of documented introductions throughout the world (Herbold and Moyle 1986). In looking at the effects on native species it is seldom possible to separate the effects of invading species from the effects of the habitat alteration that gave the exotics their chance. The difficulties are exacerbated by the scarcity of ecological information that is available to assess the effects of introduced species and of habitat modification prior to the mid 1960s. Early introductions of species, including striped bass, American shad and carp, were often authorized or performed by governmental agencies. Most recent introductions have been unintentional.

As part of the massive effort to cash in on the gold rush by giving miners something to buy in the restaurants of San Francisco, the first planting of foreign species in San Francisco Bay may have been the Mexican oyster, Ostrea chilensis (Skinner 1962). Shiploads of oysters sailed north but many oysters died on route and the business never prospered. Following the gold rush came the transcontinental railway, which provided a means to transport live animals from the east coast. The first special ore cars to bring animals from the east contained American oysters and many of their symbionts and predators. Unlike the Mexican oysters, American oysters were laid into beds in the Bay and became a part of the benthic community. It is impossible to say for many invertebrate species, particularly fish parasites, whether they are native to California or were early, unintentional imports. The native California oyster (Ostrea lurida) was initially so abundant that their crushed, windrowed shells produced a "white glistening beach that extends from San Mateo for a dozen or more miles southward" (Townsend 1893). The accumulated native oyster shells supported a long-lived local cement company. Unfortunately, the flesh of the native oyster was disdained by the newly arrived Californians (Nichols and Pamatmat 1988), so that after the native oysters had been harvested from their beds they were replaced with plantings of American oysters. The native species was "thrust into the background" (Bonnot 1935).

Frog legs were another San Franciscan delicacy that resulted in new species introductions. After hunting drove the native red-legged frog (*Rana aurora*) to the point where they could not be profitably harvested, bullfrogs (*Rana catesbeiana*) were introduced (Jennings and Hayes 1985). Overharvest of female red-legged frogs, combined with predation by the much larger bullfrog and introduced fish, are believed to have exterminated the Central Valley population of red-legged frogs (Hayes and Jennings 1986).

Crayfish were another food species whose distribution was changed as a result of human efforts. Three species of crayfish were introduced: the signal crayfish, *Pacifasticus leniusculus* var. *leniusculus*, the red swamp crayfish, *Procambarus clarki* and *Orconectes virilis*. No crayfish are reported in Native American middens of the Central Valley Patwin tribe (Schulz and Simmons 1973), but a crayfish (*P. nigriscens*) was described from specimens collected in tributaries to the South Bay. It is now extinct. Signal crayfish support a large fishery in the Delta (Kimsey et al. 1982) and the red swamp crayfish is widely distributed in the drainage.

Following the completion of the transcontinental railway in 1869, young American shad were transported from New York beginning in 1871. Common carp came into the state from Germany in 1872 through the efforts of an early aquaculturist. Trans-Pacific shipping as a path of species introduction began in 1877 when the California Fish Commission imported 88 carp from Japan. In 1874 a flood of new species followed completion of the transcontinental railway, including largemouth bass and several species of catfish and bullhead. Striped bass were introduced at Martinez in 1879 from a shipment from New Jersey (Skinner 1962).

The introduction of oysters, bullfrogs, crayfish, striped bass, and American shad was only the beginning of a long series of introductions that continues to this day. In the 19th century and the first half of this century, most introductions either were made deliberately in efforts to "improve" the local fauna from the perspective of western culture or they were made accidentally, as species hitched rides in containers with the authorized species or came attached to ships. As a result more than half the fishes in the Delta are non-native species (Herbold and Moyle 1989) and most of the benthos of the Bay is made up of exotic species (Carlton 1979; Nichols and Pamatmat 1988). New species are continuing to arrive in the Estuary, especially in ballast water of ships, as demonstrated by the recent destructive invasion of the Asiatic clam, *Potamocorbula amurensis* (Carlton et al. 1990). The presence of so many recently established species in the Estuary, combined with continual arrival of new species contributes greatly to the instability of its biotic communities and increases the difficulty of managing the Estuary to favor desired species.

#### 2.8 Exploitation

Many of the mollusks, crustaceans, and fishes of the Estuary have been heavily harvested by humans (Skinner 1962). There is little doubt that overexploitation of species such as chinook salmon, white sturgeon, softshell clam, and crangonid shrimps contributed to their declines in the early part of this century. The sturgeon and shrimp populations in fact showed dramatic recoveries once commercial fisheries were eliminated or reduced. However, as the accounts of individual species show, overharvest has played, at best, a minor role in the long-term declines of the estuary's aquatic resources.

# 3 Types of Aquatic Resources

The aquatic resources of the Sacramento-San Joaquin Estuary can be grouped into two categories based on their relationship to human interests:

1. species which are directly harvested by humans, or which support (or inhibit) the production of harvested species.

2.species which are valued for their aesthetic or biological characteristics.

The membership of each group has shifted with the abundance and use of the species individually, and with the perception of the species by different groups of people. For instance, the Sacramento splittail was harvested by Chinese-Americans, was considered a competitor with striped bass by striped bass anglers, and is now being considered for protection as a threatened species by the USFWS. The trend since the mid-1800s has been toward increasingly strict regulation of harvest, a shift from commercial to sport fisheries for most species, of regulation or mitigation for factors shown to degrade fisheries, and attempts to protect endangered species.

Directly harvested species range from the dense beds of native oyster shells that supported cement manufacture for almost a hundred years (Skinner 1962) to the valuable commercial fisheries for salmon, Dungeness crab and herring roe, to the popular sportfisheries for striped bass, catfish, and sturgeon. All of the harvested species have undergone large fluctuations in their yields (and presumably in their populations) during the 150-year history of exploitation of the Bay.

The species that affect the food supply and health of harvested species were largely unstudied until the 1960s. General ecological knowledge, current understandings of the ecological structure of the estuary, and records of conditions in prior times are the only clues to reconstructing the 'natural' status of the estuary or the steps it has passed through to get to its current state. Traditionally, aquatic biologists have distinguished between the food produced within the ecosystem being studied (autochthonous) and that carried in from other systems (allochthonous). This 'fixed carbon' may enter food chains of the Sacramento-San Joaquin estuary from five sources:

- 1. algae in the water of the estuary (phytoplankton).
- 2. algae growing on the bottom of the estuary at depths shallow enough to permit photosynthesis, at least during low tide (benthic algae).
- 3. algae and other plants of tidally inundated marshes.
- 4. fixed carbon in any form (plant or animal products, including non-living parts) carried in from upstream (riverine contributions).
- 5. fixed carbon in any form (plant or animal products, including non-living parts) carried in from the ocean (oceanic contributions).

The determination of where the fixed carbon comes from and how much of it actually enters the food web of the estuary is fundamental to estimating the quantity of animal material the estuary can support. The quantity of fixed carbon available to animals can be estimated from the sum of each of the component sources minus the potential losses to various 'sinks.' Outflow and diversion, migratory animals, and loss to sediments are some of the ways fixed carbon can be lost. Consumption by animals which die in the estuary is not lost except for the amount broken down by respiration. The respiratory rate of the animals involved and the number of trophic levels in the food chain can affect the standing crop of animal biomass. Thus, the carbon budget sets a limit on possible biomass but the structure of the animal community controls the size of the standing crop.

However, knowledge of this 'carbon budget' can give no indication of which animal species might benefit. The species composition of all trophic levels in the estuary has repeatedly changed as habitats have been altered, species have been decimated and new species have invaded. The different habitats in the estuary appear to have supported separate ecological communities, even though the abundance and species compositions have changed. By identifying the sorts of species characteristic of each part of the estuary we hope to suggest which may receive a larger share of the carbon budget in the future.

Since the 1960s, massive efforts have aimed at increasing water quality and reducing pollution of the Bay. Coincident with this has been a growing appreciation of the aesthetic and biological value of aquatic resources of the Bay and Delta. Specialized, private organizations such as Save the Bay and The Bay Institute reflect a growing appreciation of the natural values of the Bay by the public. Broader scale environmental groups, such as the Sierra Club have also increased their involvement in attempts to safeguard aquatic resources of the Bay for, largely, non-consumptive use. The activities of these groups have often focussed on the continuing decline of native fishes as well as the declines of various harvested species.

Species that have particularly drawn the attention of people working to preserve the aesthetic or ecological values of the estuary have included the spring and winter runs of chinook salmon, the Delta and longfin smelts, and the Sacramento splittail (Moyle et al. 1989). Curiously, all these species have supported fisheries in the past but have declined to such low values they are no longer economically important. Instead they are appreciated for their heritage values and as indicators of ecosystem health.

## 3.1 Fish

The fishes of the Estuary can be grouped in several ways. The only completely estuarine species of fish is the Delta smelt (Hypomesus transpacificus), although the similar longfin smelt (Spirinchus thaleichthys) occurs very rarely outside the Golden Gate; all other species maintain at least part of their population outside of the estuary. The absence of many estuarine species reflects the geologic youth of the estuary. Non-estuarine species consist of freshwater fishes with most of the populations occurring east of Carquinez Straits, marine species which are seldom found east of Carquinez Straits, and anadromous species which spawn in upstream river channels and which predictably migrate downstream through the Estuary as juveniles and upstream as spawning adults.

Freshwater species include both native and introduced species. Native species had been isolated from other regions by geological action and glacial movements; isolation and a strongly seasonal climate promoted the development of a highly endemic fauna with two characteristic types of fish: minnows which spawn only in appropriate years and spiny-rayed fishes which spawn each year and show high degrees of parental care. Most native fishes are minnows (Cyprinidae and one catostomid) which grow to very large size: Sacramento splittail (Pogonichthys macrolepidotus), Sacramento squawfish (Ptychocheilus grandis), hitch (Lavinia exilicauda), Sacramento blackfish (Orthodon microlepidotus), hardhead (Mylopharodon conocephalus), thicktail chub (Gila crassicauda), and Sacramento sucker (Catostomus occidentalis). These fish are able to defer spawning in years when little suitable spawning substrate is available and to redirect energy from reproduction into somatic growth. These species are broadcast spawners with little care given to the young aside from the selection of spawning site. Fecundity in these species is directly proportional to size. By deferring reproduction these fish increase their reproductive capacity for later years. Intensive care of young and generally wide environmental tolerances characterize prickly sculpin (Cottus asper) and Sacramento perch (Archoplites interruptus), in which the male guards a nest (Kresja 1967; Mathews 1965), and the live-bearing tule perch (Hysterocarpus traski). Sacramento perch are now extremely rare in their native range but survive as populations established in isolated, environmentally harsh habitats elsewhere. Both prickly sculpin and tule perch still live in all habitats of the Central Valley from trout streams to Suisun Bay. Native fishes in the Delta are predominantly restricted to areas dominated by Sacramento River waters (Sazaki 1975).

Many freshwater species were introduced into California from eastern North America by immigrants who wished to fish for the fishes they had known back home. These introductions were greatly facilitated by the completion of the transcontinental railway. Many eastern genera have become dominant members of the local ichthyofauna; many centrarchids (*Lepomis, Pomoxis* and *Micropterus*) and ictalurids (*Ameirus*). Common carp (*Cyprinus carpio*) were introduced during early efforts of the Department of the Interior to improve inland fisheries. More recent efforts to manage aquatic resources by changing the species composition have focused on intentionally altering trophic interactions in communities. Threadfin shad (*Dorosoma petenense*) were imported as a forage fish for

Micropterus in upstream reservoirs; inland silversides (Menidia beryllina) were brought in as a predator on abundant gnat populations in Clear Lake. Both species are now well established in the estuary. Most introduced freshwater species are more abundant in channels dominated by waters of the San Joaquin River.

Marine species can primarily be divided into those which are seasonally present and those which maintain at least part of their population in San Francisco Bay year-round. Probably because of their large populations in the ocean, seasonal species comprise many of the most abundant fishes to be found in the bay. Northern anchovy (Engraulis mordax) is often two to ten times as abundant as other fishes in the Bay and Pacific herring (Clupea harengeus) is often the second most abundant species, but abundances of adults in both species regularly fall to less than a hundredth of their peaks at certain times of year. Northern anchovy regularly enter the Bay as adults and stay for as many as nine months. Eggs and larvae of northern anchovy are also caught indicating that all life stages can use the estuary, but none stays year-round. Pacific herring enter the bay for spawning and adults are present in abundance for only a few months. Other seasonal species spawn offshore and rely on density-driven bottom currents, augmented by tidal forces, to carry their offspring into the bay. Starry flounder (Platichthys stellatus) and English sole (Parophrys vetulis) best exemplify this pattern of use of the bay. Other seasonal species can be less clear in their patterns of using the bay. White croaker (Genyonemus lineatus) most often spawn in the Gulf of the Farralones and many young enter the Bay (probably assisted by tidal or bottom currents). However, in some years adult white croaker occur abundantly in the Bay and may spawn in the shallows. Species that rely on bottom currents for transport should be adversely affected by low river outflow because low outflow cannot provide the density stratification necessary to propel ocean water into the Bay.

Resident marine species often fluctuate in their abundance in the Bay from year to year, apparently in response to the distribution of marine waters. Most of these species are benthic. Shiner perch (Cymatogaster aggregata), bay gobies (Lepidogobius lepidus), and staghorn sculpins (Leptocottus armatus) are the three most abundant resident marine species from otter trawl catches. Several other species in the same three families make up the majority of other species in this group. Like the native freshwater species, these species show high levels of parental care (either live-bearing or well protected nest sites) combined with wide environmental tolerances. This category also includes recent importations from the estuaries of Asia that were probably introduced by the discharge of ballast water from international freighters: yellowfin gobies (Acanthogobius flavimanus) and chameleon gobies (Tridentiger trigonocephalus). The survival of a transoceanic passage in ballast water probably selected the hardiest and most human-tolerant species from Asian seaports. Resident marine species generally show little response to flow and include several of the least varying fish populations in San Francisco Bay.

Anadromous species use the Sacramento-San Joaquin estuary only as a temporary passage but they have tremendous economic and aesthetic value for many people of the bay and Delta. Native anadromous species include chinook salmon, steelhead trout, and both green

and white sturgeon. Despite the extreme seasonality of outflow, the Sacramento-San Joaquin Rivers supported salmon runs in every month of the year and early settlers's accounts include descriptions of staggering quantities of salmon in the rivers. The eminent ichthyologist David Starr Jordan was one of the first scientists to enter the Central Valley. His account includes a description of salmon so densely packed that one could almost walk across the river on their backs. Other observers recorded that the abundance of spawning salmon was sufficient to deter horses from crossing streams near the McCloud River.

Early introductions from the east coast of North America included the anadromous American shad (Alosa sapidissima) and striped bass (Morone saxatilis). Populations of these species exploded from their initial plantings and rapidly spread to nearby rivers. Conditions in the rivers at the time of completion of the transcontinental railway probably favored striped bass and American shad reproduction, because their semi-buoyant eggs would not be smothered by silt from gold mining operations. Both species supported commercial fisheries in the bay about six years after their introductions. Most other early fish introductions were of nest building fishes in which the adults select the spawning site and, to varying degrees, keep the eggs clean.

Anadromous species are sensitive to a wide variety of environmental changes including upstream alterations of spawning habitat, altered access to spawning habitat, changes in flow patterns that interfere with migration, and conditions in the estuary that reduce its value as a nursery site for outmigrating young.

#### 3.2 Invertebrates

As with the fish, the aquatic invertebrates of San Francisco Bay are a mixture of both native and introduced species, with introductions outnumbering natives in most areas and habitats (Nichols 1979; Nichols and Thompson 1985). In large part the dominance by many introduced species is a reflection of what appears to have been a depauperate native fauna. Carlton (1979) quotes William Stimpson's observation in 1857 that "The Bay of San Francisco ... is nearly barren of animal life except at its entrance." However, contemporary observations on the abundance of native oysters in South Bay paint a very different picture (Skinner 1962). In 1979, almost 100 species of introduced invertebrates could be catalogued (Carlton 1979). Since then more new species have entered the ecosystem and have led to complete changes in community structure of the zooplankton and benthos, particularly in Suisun Bay and the western Delta.

New species arrive in the estuary through two major modes: as part of the transport of economically valued importations (principally oysters and their symbionts), as part of the fouling community on and in ships. More rigid regulations and greater awareness of ecological impacts have led to a slowing in the rate of intentional importation. Ironically, the eastern oyster *Crassostrea virginica* never became established in San Francisco Bay but dozens of their symbionts did. Larger ships, and the use of cargo canisters, have increased

the quantity of water carried as ballast, and most recent introductions have arrived without intentional human help. The economic and ecologic impacts of many of these species have been profound, destroying pilings, weakening dikes, fouling drainpipes, blocking water canals, as well as reducing the availability of food for higher trophic levels.

#### **3.2.1 Benthos**

Most benthic organisms in the Estuary, especially in San Francisco Bay, are introduced species. They arrived as hitchhikers with oysters, attached to ship bottoms, and in ballast water. Most of the species came from polluted bays and estuaries and survived long sea voyages. so are very hardy. As a result, a cosmopolitan fauna of hardy estuarine organisms is developing, typified by the organisms in San Francisco Bay.

The factors most affecting the abundance, composition, and health of the benthic community from year to year are outflow, both from the Sacramento-San Joaquin Delta, local runoff, and pollution (Nichols and Pamatmat 1988). The importance of pollution in controlling benthic communities has been assumed to be very high because several fisheries disappeared from South Bay as the city of San Francisco grew (Skinner 1962). In the modern estuary the water flow and pollutional loads are linked through increased concentration and mobilization of toxics. Lower outflows are also associated with lower phytoplankton biomass and hence lower productivity during periods of low flow in parts of the Bay complex. High outflows lead to lower salinities, which particularly control the species abundance and composition in shallow areas where animals are exposed to less saline surface waters.

The benthic community shows strong response both to seasonal changes of the environment and to aperiodic changes from year to year. Recruitment rates change in most species in response to salinity, temperature and a variety of other environmental conditions but migration of animals to other parts can confound studies of the effects of environmental effects on recruitment (Nichols and Thompson 1985).

#### 3.2.1.1 **Oysters**

Native oysters (Ostrea lurida) had always been extremely abundant in South and Central Bays based on the extensive build-up of shells in these areas. Middens of the California Indian tribes include large accumulations of oysters, even within the Delta where they must have been carried in trade (Skinner 1962; Hedgpeth 1979; Nichols 1979). The flavor of these oysters was disdained by European settlers and led to the first importations of foreign species into the Bay. In the latter half of the 19th century large quantities of eastern oysters were introduced and supported a large landing in the Bay Area. The eastern oyster never successfully reproduced in the Bay and, so, seed oysters were constantly needed. Transportation of eastern oysters also introduced the predatory eastern oyster drill and the new predator may have played a large role in initial declines of the native oysters (Smith and Kato 1979). Oyster landings declined from 1915 but importation of Pacific oysters (C.

gigas) from Japan boosted production after its introduction in 1930. Like the eastern oyster, the Bay Area harvest rested on constant importation of new seed oysters, so World War II brought an end to Pacific oyster culture in the Bay (Skinner 1962).

#### 3.2.1.2 Clams

All but two of the common benthic mollusks of the modern Bay are introduced (Table 1; Nichols and Pamatmat 1988). Within the Delta the dominant mollusc is the Asian clam, Corbicula fluminea, which is intolerant of saline waters while the clams of the Bay are intolerant of freshwater. Until recently the seasonal shifts in salinity reduced the clam populations in Suisun Bay except during periods of extended drought, as in 1977 when large concentrations of Mya arenaria occurred (Nichols 1985).

Clam fisheries in the Bay originally were based on dense populations of the bent-nose clam (*Macoma nasuta*) and the bay mussel (*Mytilis edulis*). Following importation of the Atlantic soft shell clam (*Mya arenaria*) with shipments of oysters in 1869, the bent-nose clams largely disappeared. Harvest rates of soft shell clams were heavy, from 1889 to 1899 landings from the bay ranged from 500 to 900 tons. Overharvest, habitat loss, and increasingly severe pollution were probably the most important factors causing the soft shell clam landings to decline to 245 tons in 1916, 68 tons in 1927 and none by 1949. Partially contributing to the decreasing take of soft shell clams may have been the increasing harvest of Japanese littleneck clams (*Tapes japonica*) that were introduced with Pacific oysters during the 1930's. Pollution led to extremely high bacterial concentrations in the Bay and from 1932 to 1953 there was a general quarantine on shellfish from the Bay. Improved water quality in recent years has led to larger sport shellfishing on the large populations of mussels, soft shell and littleneck clams that now exist in the Bay (McAllister and Moore 1982). The harvested bivalves are used both as human food and as bait for sportfish.

Table 1. Mollusks of the San Francisco Bay and Delta, based on Carlton 1979, and Gleason 1984.

# **Species**

# Year of First Description

Mytilus edulis	Native
Macoma balthica	Native (?)
Ovatella myosotis	1871
Mya arenaria	1874
Urosalpinx cinera	1890
Gemma gemma	1893
Ischadium demissum	1894
Crepidula convexa	1898
Crepidula plana	1901
Ilyanassa obsoleta	1907
Teredo navalis	1913
Lyrodus pedicellatus	1920
Petricola pholadiformis	1927
Busycotypus canaliculatus	1938
Musculus senhousia	1945
Corbicula fluminea	1946
Tapes japonica	1946
Littorina littorea	1968
Theora fragilis	1982
Potamocorbula amurensis	1986

The most recently introduced member of the assemblage appears to be an indirect result of opening up trade with the Chinese mainland, the Asiatic clam *Potamocorbula amurensis*. This mollusc was not discovered in the bay until 1986 but by 1987 and 1988 had achieved densities of up to 30,000 m<sup>-2</sup> and was distributed throughout Suisun Bay and in parts of South Bay in salinities from 1 to 33 % (Carlton et al. 1990). In Suisun Bay the previous association of benthic species largely disappeared as *Potamocorbula amurensis* multiplied. The invader had an advantage by appearing after a tremendous storm in February 1986 had removed most of the normal benthic animals (Nichols et al. 1990). Since the establishment of *Potamocorbula amurensis*, normal summertime phytoplankton blooms have failed to occur and chlorophyll a densities have remained at some of the lowest values recorded. The short time which has elapsed since the almost complete conversion of the former diverse, fluctuating benthic community into the present, spreading monoculture of the Asian clam precludes any confident guesses on the long-term effects of the clam on other aquatic resources of the Bay (see Appendix A).

#### 3.2.2 Crustacean fisheries

Unlike the mollusks, the epibenthic crustacea are still made up of many native species, particularly young Dungeness and other, smaller crabs as well as crangonid shrimps. Introduced species include the small Asian crab Rhithropaenopeus harrisi and the Korean shrimp Palaemon macrodactylus. In the upper Bay complex the epibenthos consists entirely of introduced species, particularly the crayfish Pacifasticus leniusculus var. leniusculus and var. trowbridgii which were introduced from Oregon in 1898. The red swamp crayfish, Procambarus clarki, is also widely distributed in the Delta. Other estuaries on the Pacific coast from Alaska to Baja California contain the blue mud shrimp, Upogebia pugettensis, and the ghost shrimp, Callianassa californiensis. These burrowing shrimps are sold as live bait in the Bay but there is no description of their adult populations or distributions in the Bay. Larvae of C. californiensis are a part of the zooplankton community below Carquinez Straits (CDF&G 1987).

The benthic epifauna, except for Dungeness crabs, are probably the least studied community of animals of the Sacramento-San Joaquin estuary.

# 3.2.2.1 Dungeness Crab

The most familiar member of the benthic community is the Dungeness crab, Cancer magister. For the first sixty years of this century, Dungeness crabs were an increasingly important fishery for San Francisco. Landings rose from 1-2 million pounds in the years before 1925, to 3-4 million pounds for most years between 1925 and 1945, and finally to 4-8 million pounds in most years from 1945 to 1959 (Skinner 1962). Changing oceanic conditions in 1959 caused the population and catch of crabs to drop dramatically. Some crabs were harvested within the Bay before 1900 but since then all landings have been from crabs caught outside the Golden Gate.

The absence of adult crabs, and hence a fishery for them, in San Francisco Bay has tended to obscure the abundance of this animal in the Bay; the potential of the Bay as a nursery area has been clearly shown (Tasto 1983). As much appropriate nursery habitat exists in the Bay as in the Gulf of the Farallones (500 km²) with much variability in the size of the Bay contribution to the coastal adult population (Tasto 1983b).

Dungeness crab reproduction takes place entirely at sea (Figure 5). Fertilized eggs are retained by the female on her abdominal appendages. Ovigerous females are first found in the Gulf in late September, the peak of spawning occurs during October and November (the following description is based on Reilly 1983). By January most eggs have hatched, and the zoea larvae enter the water column. Eggs apparently hatch earlier in warmer years and most hatching occurs within a two week period, the timing of which shifts from year to year. However, some of the population continues to produce new zoea as late as mid-May. Zoea larvae of Dungeness crab are the most abundant crab larvae in areas where depths exceed 30 m. The zoea show strong diurnal migrations to the surface during the night and to 25-30 m during

the day. The zoea also are absent from salinities below 32 %. Because of this sensitivity to low salinities the freshwater plume from the Golden Gate plays a large role in determining the distribution of early zoeal stages during years of high outflow (Hatfield 1983a). Zoeal stages III through V are almost absent from the Gulf of the Farallones.

After five molts the zoea transform into more crab-like larvae called megalops. Transformation to megalops begins to occur in late March or April. Megalop larvae appear to cease the diel migrations of the zoea and are found within 15 m of the surface at all hours. Megalops also differ from zoea in their preference for shallow water. Transformation of the zoea coincides with the weakening of the Davidson Current

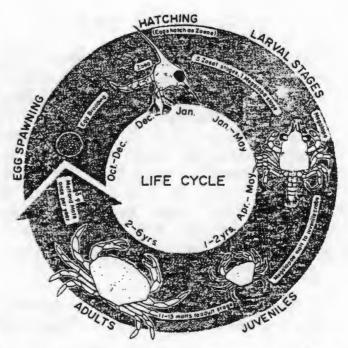


Figure 5 Life cycle of Dungeness crab in California (from Tasto 1983)

and the switch to upwelling conditions. The mechanism for transporting megalops toward the coast is unclear but is may be associated with changes in surface flow patterns either by gyres formed behind counter-clockwise gyres south of headlands or by transitory shifts in wind direction (Hatfield 1983b; Reilly 1983). However they get there, the mouth of San Francisco Bay is a major settling area (Hatfield 1983b). Dungeness crabs enter San Francisco Bay only as juveniles, molting to the new form after 25 to 30 days as megalops (Hatfield 1983b).

The number of crabs entering the Bay is primarily a function of megalop abundance and, perhaps, the strength of the landward flowing bottom current (Tasto 1983). High outflows also appear to reduce the transport of crabs into the Bay. From 1980 to 1989 otter trawls in May to June, throughout the Bay, showed much lower abundances in 1983 and 1986, two years with the highest outflows ever recorded. Dungeness crabs attained higher abundances in the Bay in years following these 'washouts,' than they had prior to them. Note that high outflows are frequently associated with *El Niño* events and other oceanic conditions that are suspected of reducing megalop abundance. Overall the abundance of crabs in the Bay has continued to vary widely through the ten years of the Bay Study, without showing any obvious trend and with quite different measures of abundance from different sampling methods (Herrgesell 1990).

Dungeness crabs enter the Bay during May or June and remain in the Bay until August or September of the following year when their carapace width is 90-120 mm (Collier 1983). Larger crabs (carapace widths greater than 100 mm) have growth rates which are significantly slower than smaller juvenile (20-100 mm carapace width; Collier 1983). The slowing in growth rates coincides with the onset of sexual maturity in the male and the beginning of emigration

from the Bay. There is also an unexplained significant difference in growth rates among years (Herrgesell 1990); which is most apparent for years of high abundance. Growth rates of juvenile crabs in the Bay is much higher than in offshore areas; growth rates off Bodega yield crab widths of only 45 mm at one year of age compared to an average of 102 mm for year old crabs in the Bay (Collier 1983). Thus, the use of the Bay as a nursery area permits much more rapid attainment of sexual maturity (Wild et al. 1983). The Bay population contributes as much as 83% of the crabs of the Central California fishery (Tasto 1983a).

Dungeness crabs are particularly abundant from Richardson's Bay upstream through Suisun Bay, showing greater abundance upstream in years of low outflow (Tasto 1983b). No crabs are found where bottom salinities are less than  $10.2 \, ^{\circ}/_{\infty}$ . and the onset of high outflows from winter storms results in a mass movement of crabs to more downstream locations. San Pablo Bay is the area of most consistently high numbers of juvenile Dungeness crabs.

Emigration from the Bay by year-old crabs is influenced by carapace width and outflow so that in years of slower growth or lower delta outflow crabs remain in the Bay longer. In general Dungeness crabs leave the Bay in August or September of the year following their arrival; so only one year class is present for most of the year, except for summer when newly settled larvae have just arrived and the older juveniles have not yet emigrated (Collier 1983). Due to the common occurrence of cannibalism in decapods a year of slow-growing, abundant juveniles may reduce the subsequent year class size.

Periodicity of Dungeness crab landings is more apparent off the Northern California coast Bay than in fishing grounds to the north (Figure 6). The cause of this periodicity has been suggested to be periodic shifts in upwelling (Peterson 1973, refuted by Botsford and Wickham 1975), cannibalism by older crabs on younger juveniles or through a predator/prey cycle with an egg-eating worm (Botsford and Wickham 1978; possible role of cannibalism argued in McKelvey et al. 1980 vs Botsford 1981). Switching in fishing effort from salmon to crabs by fisherman, and its consequences on predation effects of salmon on crabs, has also been entertained and dismissed (Botsford et al. 1982).

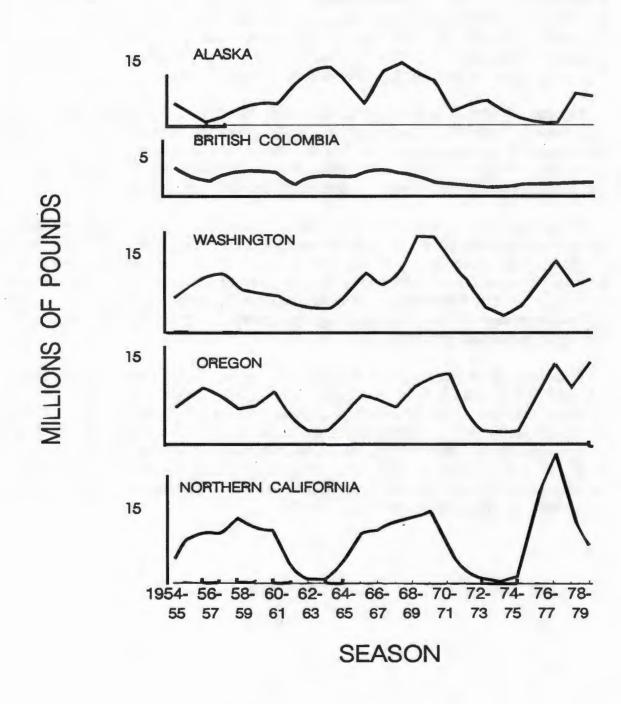


Figure 6 Crab catch in different areas of the Pacific coast fishery. Data from Tasto 1983.

A decline in Dungeness crab catch overall through the 1960s and 1970s has been clearly linked to an increase in ocean water temperatures (Huang 1972; Namias and Huang 1972; Wild et al. 1983). After 1959 mean ocean temperature near San Francisco Bay rose by about 1 C relative to the preceding period of record, the crab catch from four years later sharply declined and has stayed at consistently lower levels than occurred previously (Figure 7).

The abundance of the first zoeal stage is inversely related to temperature, with the highest densities recorded during the coldest winters. Size of the adult population is also apparently a major determinant of zoeal abundance.

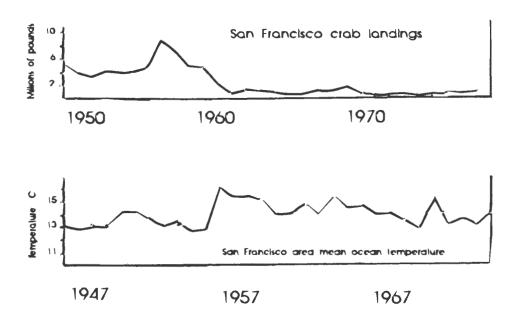


Figure 7 Landings of Dungeness crabs at San Francisco compared to mean ocean temperatures four years previously when the harvested crabs would have been planktonic larvae (modified from Wild et al. 1983).

There is little association between zoeal abundance and megalop abundance but megalop abundance is strongly tied to subsequent juvenile crab abundance. Thus, whatever controls zoeal survival in the ocean is probably the strongest control on crab abundance (Tasto 1983a).

## 3.2.2.2 Shrimp

The smaller epibenthic fauna in the Bay is dominated by four species (Crangon franciscorum, C. nigricauda, C. nigromaculata and Palaemon macrodactylus) commonly called grass shrimp by anglers and bait sellers. These species of shrimp seldom exceed 70 mm in total length. They are not used as food by most US citizens, who are accustomed to eating much larger shrimp. However, San Francisco Bay is the only North American estuary to have developed a

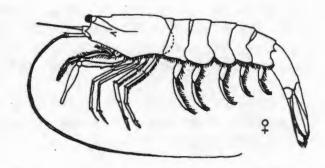


Figure 8 Crangon franciscorum (from Smith and Carlton 1975)

major fishery for these small, crangonid shrimp. In 1869, Italian immigrants collected shrimp in seines and sold them as food. The fishery shifted to the newly arrived Chinese community in 1871 because they brought better techniques and more efficient, stationary nets that caught shrimp during falling tides (Scofield 1919; Skinner 1962). The shrimp were mostly dried and exported to China. Annual landings from 1882-1892 averaged 2,270 tons but the fishery was resented by the harvesters of finfish, who objected that the nets killed large numbers of juvenile fish. Increased regulation and, probably, decreased abundance due to overharvest caused average catches to decline in through the turn of the century to only 200 tons in 1916. Through the 1920s and 1930s annual catch rose to an average of 1000 tons with a maximum harvest in 1935 of 1591 tons (CDF&G 1987b). Political upheaval in China led to abandonment of the California export fishery in the late thirties. Discovery of offshore populations of shrimp and prawns in 1952 shifted the remaining fishery out of Bay waters (Skinner 1962). In 1965 a Bay fishery for shrimp was reestablished to provide bait for striped bass and sturgeon fishers. The bait fishery takes approximately 68 to 91 tons of shrimp each year from the Bay (Siegfried 1989).

C. franciscorum (California bay shrimp) are most abundant in lower salinities with young being found in almost freshwater, C. nigromaculata (blackspotted bay shrimp) prefer salinities of 25 % or more, and C. nigricauda (blacktail bay shrimp) are seldom found at salinities below 30 % (Hatfield 1985). Ovigerous females of all species migrate to higher salinity water to release their eggs. Newly hatched zoea swim to the upper water column and are carried further downstream by outflowing surface waters (Sitts 1978). Later zoeal stages are found in lower parts of the water column and, so, are transported into the bay from offshore regions by bottom currents (Siegfried et al. 1978; Hatfield 1985). The distribution of C. franciscorum is also tied to the distribution of its most common food item, Neomysis mercedis, with more crangonids found where N. mercedis is concentrated and also showing higher feeding rates in such areas (Siegfried 1982). Diets of the species are quite variable, shifting in association with the array of prey available, with the size of the individual and in accord with the different salinity/temperature preferences of the species (Wahle 1985). C. franciscorum and C. nigricauda

are found along all of the California coast, but San Francisco Bay represents the northernmost tip of the range of *C. nigromaculata*. These shrimp are common food items for many fishes of the Bay and Delta, including: striped bass, American shad, green and white sturgeon, white catfish, and Pacific tomcod (Ganssle 1966).

The other abundant shrimp, *Palaemon macrodactylus*, was introduced from Korea (Newman 1963). *P. macrodactylus* is found only in the upper estuary, particularly Suisun Bay, Suisun Marsh and the lower reaches of the Delta; ovigerous females do not appear to migrate.

All three Crangon shrimps captured by the Bay Study show obvious responses to flow patterns (Figure 9; based on Herrgesell 1990). The tightest, and simplest, correlation is between the log-abundance of C. franciscorum abundance with the log of outflow (r=.91) for the period 1980-1988). The mechanism appears to be greater transport of post-larval shrimp into the Bay by bottom currents in years of high outflow. Greater amounts of lower salinity water also probably play an important role by providing suitable nursery habitat (California Dept. of Fish and Game 1987; Herrgesell 1990). C. nigricauda and C. nigromaculata also showed sharp increases in abundance in years of higher outflow; however, both species have maintained higher populations in the Bay during the drought years following the high outflows of 1986, while C. franciscorum has returned to low levels characteristic of other years of low outflow. The decreased food abundance in Suisun Bay in recent years (Appendix A) may also have played a role in reducing the abundance of C. franciscorum since it is the only crangonid to be found in abundance that far upstream. As a consequence of these differences in response to drought, in 1988 abundance of C. nigricauda exceeded that of C. franciscorum for the first time. A less abundant species, Heptacarpus is also apparently favored by higher salinities in the Bay since it increased in 1987-1988 to three times the abundance it had shown in earlier years. The introduced Palaemon macrodactylus, despite a distribution tied to lower salinity water, shows no apparent change in abundance with outflow. This species is more often found in association with emergent vegetation in shallow water and may not be as effectively sampled by trawls.

The interaction of direct effects of outflow on shrimp abundance with the indirect effects of outflow on their principal prey and predators could make it difficult to predict their future abundance (Armor and Herrgesell 1985). However, to date, *C. franciscorum* exhibits a straightforward response to outflow alone and the other species appear to respond more to Bay salinity.

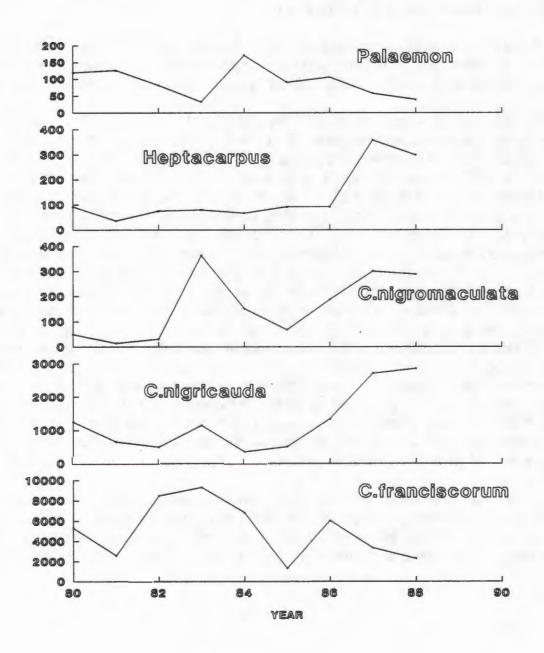


Figure 9 Abundance indices of 5 species of shrimp in otter trawls of the Bay Study 1980-1989 (data from Herrgesell 1990).

## **3.2.2.3 Crayfish**

Crayfish are harvested both commercially and for sport from waters of the Delta (Kimsey et al. 1982). The only native crayfish of the estuary, the sooty crayfish (*Pacifasticus nigriscens*), was harvested from Coyote Creek in large numbers in 1870 for consumption in San Francisco (Steinhart 1990). The population was eradicated before the turn of the century, apparently by the introduction of the signal crayfish (*P. leniusculus*), (Kimsey et al. 1982). There does not seem to have been any native crayfish in the Central Valley between the Shasta crayfish on the Pit River and the sooty crayfish around South Bay.

Signal crayfish were first found in California in San Francisco in 1898 (Kimsey et al. 1982). Signal crayfish prefer cool waters and are tolerant of salinities up to 17 %. Signal crayfish do not burrow and, so, are found most abundantly in areas with rocky bottoms or other areas where they can hide. They grow slowly, not attaining a marketable size of over 3" until two years of age (Kimsey et al. 1982). Nonetheless, they are the dominant crayfish harvested from the Delta with an annual landing of about 250 tons in the early 1980s.

Red swamp crayfish (*Procambarus clarki*) are the principal cultivated crayfish in their native Louisiana and in other states. Their value as a food item is largely due to their very rapid growth; they can reach marketable size of 3" in three months. They were first introduced into California at Los Angeles in 1924 and have now spread through most of the state (Kimsey et al 1982). Red swamp crayfish prefer warmer waters than *Pacifasticus*, and are frequently found in rice fields and in sloughs with abundant emergent vegetation. They dig a 2" diameter burrow as deep as 40" into dikes and streamsides. By plugging the burrow with mud they are able to survive complete dewatering of the stream or rice field. They can also survive in stagnant waters by using atmospheric oxygen and can tolerate salinities as high as 30 %. Another burrowing crayfish, *Orconectes virilis*, escaped into California waterways in 1940 from holding ponds at Chico State College. Both species burrow and eat young rice shoots and are considered pests by rice farmers.

The distribution and abundance of the various crayfish, and the effects of environmental factors, have not been investigated.

## 3.3 Primary producers

### 3.3.1 Bacteria

Bacteria play an essential role in both the food webs and the biogeochemical cycles of estuaries. On a functional basis, several groups can be recognized. Heterotrophic bacteria are dependent on organic material for their carbon and energy, whether these materials are produced within the estuary by primary producers such as phytoplankton, or are introduced into the estuary by, for example, river flows, wastewater, or tidal marsh export. Aerobic heterotrophs require oxygen for their metabolism and are found in the water column and surface sediments. Anaerobic heterotrophs live in anoxic sediments and oxygen-free microzones surrounding detrital particles in the water column. These anaerobes utilize nitrate and sulfate as a source of oxygen, producing reduced substances such as methane, ammonium, and hydrogen sulfide. One of these anaerobic pathways involves the formation of nitrogen gas, an important process known as denitrification. Chemoautotrophic bacteria, in turn, use these reduced products as an energy source and carbon dioxide as their carbon source. As a result of their metabolism, some of the reduced substrates they depend on for energy are oxidized back into nitrates and sulfates. Finally, photoautotrophic bacteria use light as their energy source and carbon dioxide as their carbon source; in contrast to plants, however, these bacteria use reduced compounds instead of water as a hydrogen donor.

### 3.3.2 Protozoans

The Protozoa are single-celled organisms that are generally heterotrophic, subsisting on organic material, although some may derive supplemental energy from photosynthesis. Most are holozoic or particle-feeders that consume bacteria, algae, particulate organic matter, other protozoans, and even smaller metazoans. The common mode of reproduction is mitosis and binary fission. Aside from those forms that are internal parasites of other animals, most protozoans in temperate coastal areas are ciliates or flagellates. Ciliates are usually found in conjunction with high concentrations of decaying organic matter — for example, in or near the sediments — but one group, the Tintinnidae, is common to the pelagic zone. The genus *Tintinnopsis*, for example, is characteristic of shallow coastal waters and has at times been observed at high concentrations throughout the Bay and in the western Delta (Sitts and Knight 1979; Ambler et al. 1985).

# 3.3.3 Algae

# 3.3.3.1 Phytoplankton

Phytoplankton are the small, usually microscopic, algal forms that occur in every water body. They are primarily photosynthetic, but some may supplement energy needs by assimilating dissolved organic compounds and even, in some cases, detrital particles or other organisms.

Phytoplankton are extremely diverse in terms of taxonomic status, habit and life cycle, and this diversity is no less characteristic of estuarine phytoplankton communities.

The lower reaches of estuaries are usually dominated by diatoms; dinoflagellates are less abundant but can be important at times. Smaller flagellated forms, such as cryptomonads, can also be numerous. Neritic diatom species from adjacent coastal waters penetrate estuaries to varying degrees, depending on their capacity to withstand reduced salinities. Upstream, estuarine species that are of minor importance in fresh or marine waters may predominate. Further upstream, the estuarine communities give way to freshwater assemblages.

The major algal group in estuaries is the class Bacillariophyceae, the *diatoms*. Diatoms are usually solitary, although filamentous and colonial forms also occur. Their cell wall, or *frustule*, is composed of silica with an organic coating. They contain both carotenoids and fucoxanthin, which gives most of them a golden-brown color. Planktonic species may be *holoplanktonic* -- able to complete their life cycle independent of the bottom; *meroplanktonic* -- pelagic for only a short portion of their life cycle; or *tychopelagic* -- usually attached but forcibly torn from their usual habitat. Thus, certain species may be collected from the water column, from sediments, or off of some substrate. Planktonic cells often have morphological adaptations such as flattening or spines that slow their sinking rates.

A second important group is the class Dinophyceae, the *dinoflagellates*. These are unicellular organisms with two flagella that are common in estuarine waters, although not so prevalent as diatoms. They are usually photosynthetic, but consumption of dissolved and particulate organic matter is a well-developed mode of nutrition in some species. Some dinoflagellates are "armored" with thick *thecal* plates that may form conspicuous wing-like projections. Several marine dinoflagellates are bioluminescent. Dinoflagellates also produce blooms or "red tides" in which the waters are colored by the high concentration of cells. Some of these blooms are associated with toxin production and may be responsible for fish or invertebrate kills. Other blooms may kill few marine organisms, but the toxin can become concentrated in shellfish and pose a later hazard to humans consuming the shellfish.

Small flagellated algae form a third important group in the estuary. These are primarily members of the Cryptophyceae, the *cryptomonads*. Cryptomonads have asymmetric, flattened cells with two flagella. A wide range of pigmentation can be found in cryptomonads, including red, blue and green. Species occur from freshwater to marine habitats, and some of them are tolerant of quite wide salinity fluctuations. Although most are photosynthetic, some can feed on dissolved organic matter. In many environments, cryptomonads "fill in" algal communities between bloom periods, although they are usually not capable of forming massive blooms themselves -- probably because of susceptibility to grazing.

#### 3.3.3.2 Benthic microalgae

Benthic microalgae -- known also as the *microphytobenthos* -- occur primarily in the upper 1 cm or so of sediments, although they can be found alive at greater depths. The benthic

microalgal flora is a diverse assemblage of diatoms, blue-green algae, and flagellates, usually dominated by pennate diatoms. Photosynthesis is the primary nutritional mode. Benthic microalgae are much less sensitive to high light intensities than phytoplankton, so that exposure to full sunlight in intertidal areas is generally not harmful. Many benthic diatoms also have an endogenous circadian rhythm in which they migrate vertically through the sediments; diel migration enables them, to some extent, to control exposure to light. These migrating algae often leave a trail of mucus, which may serve as nutritional support for other microorganisms. The algae themselves are ingested and assimilated by many epifaunal and infaunal deposit feeders. Typical benthic microalgae include species of Navicula, Nitzchia, Gyrosigma, and Cylindrotheca. Meroplanktonic taxa such as Melosira are often found alongside these truly benthic forms.

Sediments in the San Francisco Estuary contain typical estuarine species such as Nitzchia acuminata and N. pusilla in the South Bay shoals (Nichols and Thompson 1985), as well as species characteristic of more saline and oligohaline environments in Central Bay and Suisun Bay, respectively. The distinction between benthic microalgae and phytoplankton is not always clear. In Suisun Bay, for example, phytoplankton such as Thalassiosira decipiens may accumulate on sediments as their bloom in the overlying water terminates. In the central Delta, Melosira granulata, which has bloomed in the water almost every year since 1979, is also an important component of the benthos at times.

## 3.3.3.3 Macroalgae

The macroalgae -- often known as seaweeds -- are a diverse group of large algae. Estuaries are usually colonized by marine species, and freshwater species predominate only near the head. In the middle reaches of estuaries, there may be a few species confined to brackish water. Hard substrates usually support the greatest diversity of macroalgae. In San Francisco Bay, these are most common close to the Golden Gate. But even though diversity decreases toward the soft sediments of southern South Bay, San Pablo, and Suisun Bay, the biomass of individual species can still become substantial. Species diversity usually decreases upstream, with green algae (Chlorophyta) having the widest distribution within the estuary. The most common green macroalgae in estuaries include Enteromorpha, Ulva, Ulothrix, and Cladophora, among others. The brown alga Fucus and the red alga Polysiphonia also have a wide distribution in estuaries.

Josselyn and West (1985) have reviewed the occurrence of macroalgae within the San Francisco Estuary. Over 160 species have been noted. As in other estuaries, the most common forms are green algae belonging to the genera *Enteromorpha*, *Ulva*, and *Cladophora*. *Ulva* and *Enteromorpha* spp. can form extensive mats on estuarine mud flats. *Polysiphonia*, a common red alga in San Francisco Bay, also can form nuisance blooms.

# 3.3.3.4 Seagrasses

Seagrasses are marine angiosperms characteristic of tropical and temperate estuaries. Although there are a dozen or so higher plant genera that can function normally and complete

their life cycles in saline waters, the most widely-distributed dominant in temperate estuaries is Zostera or eelgrass. Seagrass beds may consist of only a few isolated plants or clumps of plants, or may be dense and extensive. Bottom morphology and sediment dynamics are critical in establishing the range and density of seagrass beds. Seagrasses often have significant quantities of attached epiphytes associated with them, and they can provide both food and cover to a number of crustacean and fish species.

## 3.4 Zooplankton

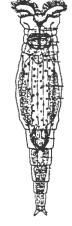


Figure 10 Ventral view of typical rotifera (modified from Pennak 1953)

### 3.4.1 Rotifers

The Rotifera are small metazoan invertebrates most common in fresh waters, although a few purely marine forms are known. The overwhelming majority of species are sessile and associated with littoral substrates, but about 100 species are planktonic and form a significant part of freshwater zooplankton communities. The anterior end is ciliated, and the movement of these cilia functions both in locomotion and in directing food particles toward the mouth. Omnivorous feeding on both living and dead particulate organic matter is typical, but some species prey on protozoa, other rotifers, and other zooplankton. Reproduction is typically by parthenogenetic females, occasionally punctuated in some species by sexual reproduction involving short-lived males. Dominants in the Bay-Delta include the common genera Synchaeta, Keratella, and Brachionus.

At salinities greater than 5-10  $^{\circ}/_{\infty}$ , Synchaeta is the most common rotifer, so it is common in South Bay and its distribution in the rest of the Bay varies seasonally (Ambler et al. 1985). It is usually found in abundance only in areas with high densities of chlorophyll a (Ambler et al. 1985). In the upstream portions of the estuary rotifer populations undergo seasonal cycles that appear to be a result of seasonal changes in salinity (Chadwick 1972). Thus, Keratella

is abundant in the western Delta only in the spring when salinities are minimal (Chadwick 1972) and in the fall *Synchaeta* dominates (Siegfreid et al 1978). In the eastern Delta, beyond usual salinity intrusion limits, a rich rotifer assemblage occurs, *Keratella* being most abundant in an array of eight genera of herbivores, omnivores and one predatory genus, *Asplanchna* (Orsi and Mecum 1986; Herbold and Moyle 1989). However, many of the additional rotifer species comprising the richer assemblage of the Delta are benthic rather than planktonic (Chadwick 1972).

#### 3.4.2 Crustaceans

Crustacean zooplankton have been the subject of much more study in Suisun Bay than any other area because of the importance of N. mercedis as a principal food of young striped bass

(Turner 1966a; Siegfried and Kopache 1980; Knutson and Orsi 1983; Orsi and Mecum 1986; Obrebski 1991). Studies describing copepod species and documenting their distribution have also contributed to general understanding of trophic dynamics in the Estuary (Orsi et al. 1984; Ferrarri and Orsi 1984). Laboratory studies arising from field observations have examined factors affecting the links between trophic levels (Meng and Orsi 1991).

Studies of plankton in the Delta and in the Lower Bay have been much more scarce. The only recent publication describing Delta zooplankton were Orsi and Mecum (1986) which ended with a recognition that invading species of copepods had drastically changed the zooplankton community from what they were describing. Evidence presented to the State Water Resources Control Board hearings (CDF&G 1987) described long-term trends in Delta zooplankton through 1985. Very little has been published on riverine plankton and what little has been done focused more on phytoplankton (Greenberg 1960). Analyses of recent Delta zooplankton data are in preparation (Orsi et al. 1991). Zooplankton in Central, South and San Pablo Bays were described on the basis of the years 1978-1981 (Hutchinson 1980a, 1980b, 1982a, and 1982b; Ambler et al. 1985). Zooplankton distribution and population dynamics in coastal waters near San Francisco Bay have been studied as part of intensive studies of Dungeness crab biology (Reilly 1983; Hatfield 1983a).

## 3.4.2.1 Cladocera

Cladocera, or water fleas, are often the most abundant crustacean in freshwater. Most species are widely distributed throughout large areas, including all of the species reported from the Sacramento-San Joaquin Estuary. cladoceran populations show strong seasonality in and pronounced changes in abundance reproductive habits in different seasons. During the warmer months of the years reproduction is by parthenogenesis and the females give birth to fully functional juveniles. Gestation times are around two days and generation times are usually less than one month. Thus, a population can rapidly increase under favorable conditions. Males and the larger eggs which they fertilize (called ephippia) are usually produced as temperatures and photoperiods decline. fertilized ephippia sink to the bottom and are the

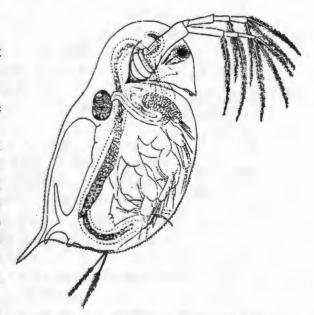


Figure 11 Daphnia pulex. (modified from Pennack 1953)

primary method of overwintering for these animals. Ephippia are resistant to desiccation and, by passive attachment to waterfowl, are responsible for the wide distribution patterns of most Cladocera. Parthenogenetic reproduction permits successful colonization of new habitats by transport of a single ephippium.

Cladocera swim by sudden contractions of their antennae and are efficient feeders on a wide variety of materials from throughout the water column, including phytoplankton, bacteria and colloidal suspensions. They are widely recognized as an important level for food chains in the upper portions of estuaries (Haertal and Osterberg 1967).

Cladocera seldom occur in abundance in areas where salinity is greater than 1 %, but they are abundant in waters of the Delta. All cladocerans have the bulk of their populations at conductivities under 1000 µmhos (Figure 12). Of the three most commonly collected species of Cladocera, Bosmina is the most abundant genus throughout the Delta, Daphnia is less abundant and more of its population is found within a narrower range of salinities, Diaphonosoma is least abundant but a larger proportion of its population is found at higher conductivities (Figure 12). Bosmina is the most widely distributed genus, occurring in measurable densities in Suisun Bay in all but two of the years since sampling began in 1972 and in 6 of the 10 years of sampling in Carquinez Strait (unpublished data CDF&G). Abundance of Bosmina is at least partly controlled by the abundance of the predaceous shrimp N. mercedis (Orsi and Mecum 1986). Daphnia also has been found in Suisun Bay in all but two years of the sampling, but it occurs at extremely low densities (less than 10 per cubic meter in half of the years. Daphnia was found at Carquinez Strait in only 4 of the 10 years of sampling there. Densities of all three species are highly correlated with temperature and, excluding Diaphanosoma, with chlorophyll a concentration (Orsi and Mecum 1986). These associations with temperature conform to the greater abundance of all species in the San Joaquin River, because it is generally warmer than the Sacramento River and supports higher densities of phytoplankton (Orsi and Mecum 1986). Diaphanosoma has the most restricted distribution of the three abundant native cladocerans; it has never been collected in samples taken at Carquinez Strait and when collected in Suisun Bay its mean density has never exceeded 45 per cubic meter.

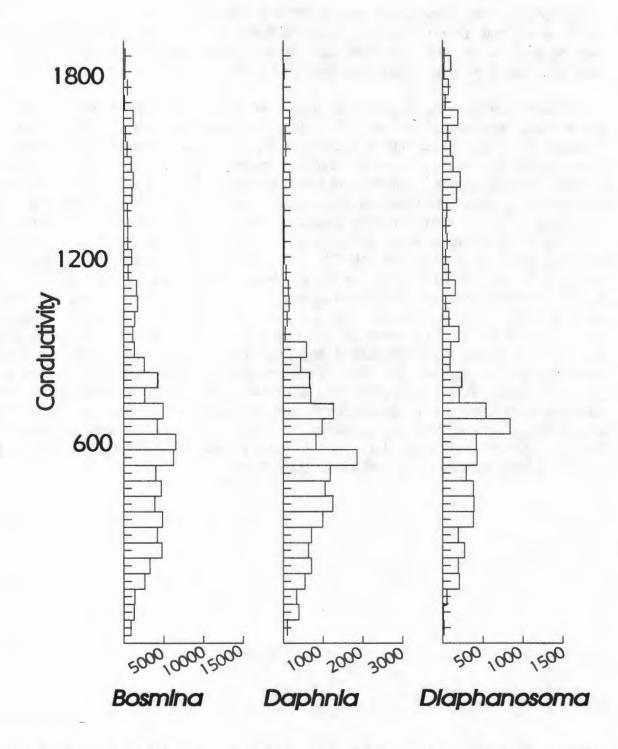


Figure 12 Mean catch (number per cubic meter) of three species of Cladocera at different ranges of conductivities. Ranges of conductivities are represented by the low value within each range. (data from CDF&G).

## 3.4.2.2 **Copepoda**

Copepods are small crustaceans that feed and live in the water column like Cladocera but which are evolutionarily derived from oceanic animals so that their greatest diversity and abundance is in salt water. Harpacticoid copepods are predominantly benthic copepods and, so, not sampled very efficiently in studies of zooplankton. Calanoid copepods replace Cladocera in most of the Bay below Chipp's Island, Cyclopoid copepods are generally found in more freshwater habitats with Cladocera. Calanoid copepods swim in a slow, smooth gliding pattern by movements of their mouthparts occasionally punctuated by sudden jerks propelled either by the same mouthparts or by their legs and antennae. Cyclopoid copepods move by a series of leaps propelled by flattened appendages on the abdomen and their first antennae, followed by a period of passively sinking (Williamson 1991). Cyclopoids respond to disturbance by escape responses that may involve hops at velocities up to 4 times that used in normal locomotion. Copepods are the primary food for many small fish in the Estuary. including young striped bass.

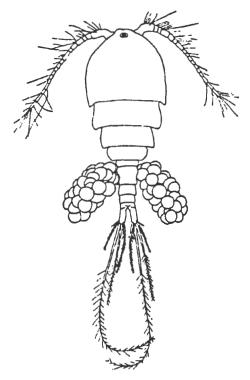


Figure 13 Typical copepod, with egg sacs. (Modified from Pennak 1953)

All copepods in the Estuary are sexual and cannot reproduce parthenogenetically, unlike the rotifers and water fleas. However, females store sperm so a single mating can allow a female to develop a series of fertilized eggs (in the Calanoidea) or of eggsacs (in the Cyclopoidea). Development and incubation are generally rapid with complete development attained within one or two weeks in most species and with hatching of eggs taking from 12 hours to 5 days. After hatching young copepods go through a series of molts as nauplii similar to other crustacea and a further series of copepodid stages which resemble the adult. Declining temperatures and shortening photoperiods may prompt the production of thicker shelled, over-wintering eggs or larval stages may form cysts and fall to the bottom. Although most copepods are widely distributed, the requirement for sexual reproduction has apparently led to most freshwater and estuarine species being somewhat less widely distributed than most species of Cladocera. However, recent introductions of several species of copepods argues that this larger cargo ships have reduced the effectiveness of this barrier.

In the Sacramento-San Joaquin estuary the abundant native copepods are sharply separated by salinity and season (Ambler et al. 1985). The characteristic species and the conductivity of the water at which they occur are shown in Figure 14. The genus *Acartia* contains two species which undergo complementary seasonal successions of abundance in South Bay (Ambler et al. 1985). Another species of the lower Bay (*Oithona davisae*) is not included in the figure but

peaks in abundance in the autumn (Ferrari and Orsi 1984). In the late 1970's and 1980's the upstream populations of native copepods in the upper Bay and Delta were disrupted by invasions of species unintentionally introduced from the China, Sinocalanus doerri and Pseudodiaptomus forbesi. Native copepods, particularly Eurytemora affinis, suffered large declines in abundance while these species have increased in abundance (Orsi et al. 1983; Carlton 1986; Orsi and Mecum 1986). In the Delta the dominant copepod genus is Cyclops.

## 3.4.2.3 Mysid shrimp

The opossum shrimp, Neomysis mercedis, is found in greatest abundance in Suisun Bay and the western Delta, although it is found as far upstream as Sacramento (Orsi and Knutson 1979) and in the lower reaches of the Mokelumne River (Heubach 1969). The family Mysidae is related to scuds and sowbugs, but is unusual in that its members are excellent swimmers and spend most of their lives in the water column. The family is found throughout the northern hemisphere and has been widely studied because they are important items in the diets of most fish where they occur and they have been found to be very useful in monitoring the effects of toxics. Neomysis mercedis can be found from Alaska to just below Point Conception, California.

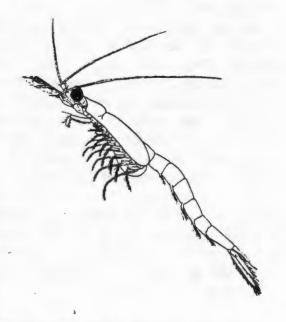


Figure 15 Mysid shrimp. (modified from Pennak 1953)

Opossum shrimp received their common name because females carry their eggs and young in a pouch at the base of the last two pairs of legs. Young are retained until the larvae are fairly well developed.

Neomysis mercedis is found in the diets of almost all fishes of the Delta (Heubach 1963; Turner and Kelley 1966; Radtke 1966; Turner 1966 a,b; Turner 1967; Moyle 1976; Smith and Kato 1979; Stevens 1979; Moyle et al. 1986). In studies prior to 1974 these shrimp were identified by the synonymous names N. atschwanensis and N. intermedia (Simmons et al. 1974a,b). Unlike other elements of the zooplankton, the biology of N. mercedis has been widely studied and described. Another rare mysid shrimp occurs in the freshwaters of the Delta, Alienacanthomysis macropsis, and one small mysid (Deltamysis) has been found throughout Suisun Bay and the Delta (Orsi and Knutson 1979; Herrgesell pers. comm.), but there are no reports on the biology of either.

Early studies of the distribution of N. mercedis found that it concentrated in areas with higher chloride concentrations (2 %), particularly the western Delta and, to a lesser extent, the San Joaquin River near Stockton (Turner and Heubach 1966; Heubach 1969). This observation was

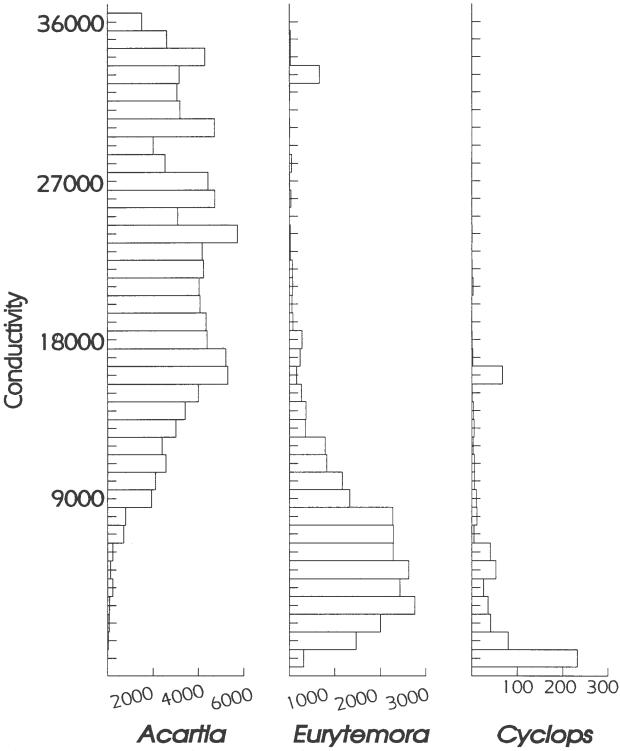


Figure 14 Mean catch (no./ cubic meter) of three species of Copepoda at different ranges of conductivities. Ranges of conductivities are represented by the lowest value within each range (data provided by CDF&G).

initially interpreted as evidence that salinity was a primary factor governing the distribution of the opossum shrimp. Later laboratory studies have shown that the optimal salinity for this species is near 10 %, at which it is never found in great numbers; while the salinities at which it occurs in its greatest densities (1-4 %) are probably osmotically stressful (Sitts 1978).

The upstream limits of *N. mercedis* abundance appear to be set partly by light intensity. Ninety percent or more of the adult population is found at depths where light intensity is less than 10-5 lux (Heubach 1969). In most delta waters depths must be greater than 3 m to provide sufficient attenuation of sunlight. In areas where the channels are not at least 3 m deep *N. mercedis* is absent (Heubach 1969). Similarly, in channels with shallow sides, *N. mercedis* is found only in the deeper, central parts of the channel. These conditions are probably one reason for the greater abundance of *N. mercedis* in the deeper stations (Heubach 1969). At night these patterns of shrimp abundance in relation to depth break down and *N. mercedis* is found uniformly distributed throughout the water column (Heubach 1969; Sitts 1978; Siegfried et al. 1979). Siegfried et al. (1979) used a smaller mesh net than earlier studies, which permitted them to catch representative numbers of young shrimp. They found that shrimp less than 3 mm long did not seem to respond as strongly to light intensity as larger shrimp, so that small shrimp were common in the upper parts of the water column (they may even be positively phototactic).

Net flow velocities greater than 0.12 ms<sup>-1</sup> appear to prevent *N. mercedis* from maintaining its position in a channel (Turner and Heubach 1966; Orsi and Knutson 1979) and, thus, are barriers to the upstream migration of the shrimp. Operation of the cross-delta channel in 1964 provided evidence of the importance of net flow velocity (Turner and Heubach 1966). Before the gates to the channel were opened flows in the Sacramento River at Isleton were over 0.12 ms<sup>-1</sup>, and flows in the cross-channel were less than 0.12 ms<sup>-1</sup>; *N. mercedis* were absent from the Sacramento River and present in the Mokelumne River. After the gates to the channel were opened the flow rates switched between the two sites, as did the distribution of *N. mercedis*. Looking throughout the Delta, Turner and Heubach (1966) found that *N. mercedis* were seldom found in channels with net flows over 0.12 ms<sup>-1</sup>. During the drought of 1976-77 the barrier effects of net flow were weakened by the greatly reduced outflows and, as a consequence, *N. mercedis* were found much further upstream than usual (Knutson and Orsi 1983).

In addition to their diel vertical migrations in response to light, *N. mercedis* also migrate in response to tidal flows. Adults tend to remain on the bottom during ebb tides and rise into the water column during flood tides. Combined with the landward-flowing, density-driven current on the bottom, this behavior tends to move the adult shrimp up into the more freshwater parts of the estuary (Siegfried et al. 1979; Orsi and Knutson 1979). The greater occurrence of young shrimp near the surface of the water column tends to move them downstream from the adults and into the entrapment zone (Siegfried et al. 1979; Orsi and Knutson 1979). The entrapment zone also concentrates nutrients, phytoplankton, and suspended detritus (Arthur 1975; Ball 1975; Arthur and Ball 1979), making it an ideal nursery area for *N. mercedis* (Siegfried et al. 1979). The results of Siegfried et al. (1979) would suggest that young *N. mercedis* would continue to be carried by surface currents on through the entrapment zone and down to the sea.

Studies through several years (Orsi 1986) indicate that there is less of a difference in vertical migration between different ages of *N. mercedis* than reported by Siegfried et al. (1979), whose study encompassed only one year. Smaller individuals are more likely to migrate into the more lighted surface waters on flood tides, when they would be carried upstream. The greater occurrence of smaller *N. mercedis* in landward-flowing flood tides explains their observed scarcity in waters seaward of the entrapment zone. Seaward of the entrapment zone, greater water clarity allows deeper light penetration and most *N. mercedis* of all sizes are in the landward-flowing, bottom, density current. Within the entrapment zone, water clarity is low and most of the population moves up into the area of neutral flow between the surface, river outflow layer and the deeper, density currents.

Neomysis mercedis undergoes extremely large seasonal fluctuations in abundance, from mean densities in winter of less than  $10\text{m}^{-3}$  to almost  $1,000\text{m}^{-3}$  in spring. Three main bouts of reproduction occur each year, but the high densities of late spring overlap the smaller peaks (Siegfried et al. 1979). The overwintering population consists mostly of large, adults, which breed in the early spring. The new generation grows at the same time as the populations of phytoplankton are multiplying. Fecundity is directly related to size, but females in late spring produce more young than females of the same size in early spring (Heubach 1969). Reproduction by the early spring generation produces the large concentrations of N. mercedis in late spring. In addition to the changing relationship of length with fecundity, N. mercedis matures at smaller sizes in summer than in winter or spring. The summer population produces the overwintering generation.

High temperature (Heubach 1969; Siegfried et al. 1979), low dissolved oxygen (Orsi and Knutson 1979; Turner and Heubach 1966), predation (Heubach 1969) and seasonal declines in temperature phytoplankton (Orsi and Knutson 1979) have all been suggested as the force behind the fall decline in *N. mercedis* abundance. Hair (1971) found that the upper lethal temperature limit for *N. mercedis* was 24.2-25.5° C, although levels of dissolved oxygen can apparently affect the degree of stress caused by high temperature (Orsi and Knutson 1979). In the San Joaquin River at Stockton, near-lethal temperatures are combined with low dissolved oxygen, and it may be the combination, rather than either factor alone, that decimates that population (Orsi and Knutson 1979). Heubach (1969) observed that the greatest numbers of young striped bass, which eat primarily *N. mercedis*, are in the same area as their prey but was unable to quantitatively test this hypothesis because he had no measure of bass abundance.

The diet of *N. mercedis* varies by size, through time, and by location within the estuary. Larger individuals usually prefer copepods, particularly *Eurytemora affinis*, while smaller individuals (<3 mm total length) primarily consume phytoplankton and rotifers (Baldo Kost and Knight 1975). Like most mysids (Foulds and Mann 1978; Mauchline 1971), *Neomysis mercedis* is primarily a filter-feeder, taking what passes through its filtering current, rather than chasing individual items. However, there is clear selection of the material ingested from that caught on the filter pads. When rotifers are abundant, the juvenile *Neomysis* take more of them, and the juveniles probably derive most of their energetic gain from that part of their diet (Siegfried and Kopache 1980). Even among the phytoplankton species, whose energy contents are much less

than those of animal material, there is strong evidence of selection. From March to May 1976, Skeletonema was by far the dominant diatom in the western Delta but the guts of Neomysis contained mostly Melosira or Thalassiosira. Similarly, from June to November the only common diatom in gut samples was Thalassiosira although it was a very small part of the phytoplankton assemblage present. Larger individuals fed primarily on zooplankton and showed strong prey selection. Copepod nauplii were the most abundant component of the zooplankton assemblage but were rarely consumed. Neomysis guts predominately contained Eurytemora affinis, harpacticoid copepods, and rotifers.

### 3.4.2.4 Other Crustacea

A number of other types of crustacea have been collected in the course of sampling plankton in the estuary. Oceanic species of krill (Euphausidae) enter the Bay in greater numbers when outflow is high, probably as a result of El Niño effects or the greater strength of bottom currents (CDF&G 1987). The three most commonly collected species are Nematoscelis difficilis, Thysanoëssa gregaria, and Nyctiphanes simplex. Central Bay is usually the only area where these shrimp occur in abundance but during periods of high outflow they have been found in channel stations up to Carquinez Straits and the far south end of South Bay (CDF&G 1987). N. simplex is normally found south of Point Conception but appears to have been brought further north by El Niño conditions in 1983.

Larvae of the ghost crab (Callianassa californiensis) are also a common feature of the zooplankton in Central Bay, but they are much less common elsewhere (CDF&G 1987). Young larvae appear to be carried out of the Bay in the surface water by high flows and older larvae enter the Bay on bottom currents. The net effect of high outflow is to reduce the abundance of ghost crab larvae because the number transported out of the Bay by high outflows is greater than that carried in by the consequently stronger bottom currents. Years of low outflow cause more of the crab larvae to remain in the Bay and larval populations are therefore higher. Because the status and dynamics of the adult population is entirely unknown it is impossible to say whether the greater retention of small larvae in the Bay during dry years produces a larger adult population than the greater immigration of larger larvae into the Bay in wet years (Strathman 1982).

In Suisun Bay and, to a much lesser extent San Pablo Bay, larvae of the introduced pea crab Rithropaenopeus harrisi are caught in plankton samples. Adults are known to occur as far upstream as Stockton but breeding must occur in fresh water (Barnes 1980). R. harrisi was first reported from the estuary in 1940; how it was transported from it's native range along the Atlantic coast is unknown. High summer outflow, when the larvae are planktonic, is inversely correlated with larval abundance (CDF&G 1987).

## 4 Trends expected to affect aquatic resources

### 4.1 Global warming

Global warming is the long-term trend most likely to have the greatest impact on aquatic resources of San Francisco Bay. The debate surrounding the evidence for global warming and the estimates of rates and degrees of warming have attracted wide public interest. Academic, federal, state, and private studies have generally concluded that global warming is at least very likely and that certain aspects may be unavoidable (USEPA 1983, 1988; California Energy Commission 1989; Gleick and Maurer 1990; Regier et al. 1990). Although the recent extreme weather conditions in California may have little to do with global warming, their effects on aquatic resources of the Bay and Delta are similar to some of the effects expected to be associated with a global warming trend.

Global warming is apt to alter ecosystems via three mechanisms (Regier et al. 1990): direct alteration of the physical environment of animals, changes in the operation of physical and biotic linkages within communities, and alterations in the physical environment as a result of human response to the effects of global warming. The first mechanism is probably more important for terrestrial systems than aquatic ones, due to the heat-buffering capacity of water. One possible direct effect of increased temperature is that of decreased availabilities of oxygen in warmer waters; this has been proposed as a mechanism for explaining the variable success in introducing striped bass (Coutant 1981, 1990) Thus, global warming may pose an added difficulty for recovery efforts for the striped bass fishery in San Francisco Bay. The degree of human manipulation of the physical habitat of San Francisco Bay makes it difficult to separate the effects of humans from human response to global warming from ecosystem mechanisms.

A second major effect of global warming on the aquatic life of the Bay will be reduction or loss of shallow water and intertidal habitats as sea level rises (Gleick and Maurer 1990). Sea level is estimated to rise between 13 cm and 55 mm by the year 2025, and by 24 cm to 1.17 m by the year 2050 (USEPA 1983). Unambiguous effects of rising sea level are not expected to be felt until 2020 when rates of rise are expected to increase from this century's average of 1-1.5 mm/year to probable rates of 3 to 15 mm/year in the next century (USEPA 1983). Intertidal habitats of the South Bay that lie between present mean low water and the lower limit of urban development are almost certain to be lost with any appreciable sea level rise, as they are apt to be converted to dikes and other flood control structures. Wetland habitats around San Pablo and Suisun Bay may be lost entirely due to flood control, but the reduced intensity of urban development in these areas may permit some to become intertidal habitats. Passive sea level rise will certainly cause problems but political pressure to isolate or convert wetlands by dikes will be amplified by the greater incidence of large storms that will accompany global warming trends (Gleick and Maurer 1990). These storms are expected to show as much as a tenfold increase in frequency under a global warming scenario of only a 15 mm rise in sea level.

Sea level rises and global warming will entail changes in the mean salinity and in the pattern of annual changes in salinity that characterize the northern reaches of the Bay. Sea level rises

will push salt water further upstream and this effect would produce mean isohaline profiles 15 km upstream; increased storms will provide more freshwater outflows for a net effective upstream migration of salinity profiles of only 10 km (Williams 1989). Direct effects of increased salt water intrusion are expected to interact with substantial alterations in patterns of freshwater inflow. Rising sea levels are apt to lead to massive levee failures within the Delta. Agricultural practices within the Delta have reduced the levels within Delta islands by as much as 10 m, so that levee failures will serve to transform the Delta into an inland arm of the Bay rather than back to its primitive status as a marsh. Sediments would tend to accumulate in the upper bay and Delta as the ratio of sea water inflow to freshwater outflow shifts towards marine influences. Stronger and more frequent wintertime storms will lead to increased erosion of the perimeter of the lower bay and make these sediments available to landward flowing bottom currents. Contrarily, increased storm frequency and severity will increase transport of sediment out of the Delta during the winter. Human responses to these climatic and environmental changes could include construction of a wide variety of protective structures, probably at Carquinez Straits or in the western Delta. These massive and poorly quantifiable changes in aquatic habitats of San Francisco Bay and Delta will have similarly massive and poorly quantifiable effects on aquatic resources.

The effects of a global warming pattern on precipitation in California are unpredictable, except that warmer temperatures will cause a greater percentage of precipitation to fall as rain rather than snow (California Energy Commission 1989). The more rapid runoff of rainwater will tend to restore the seasonality of outflow through the estuary. Even if precipitation stays the same or increases, a higher percentage of winter runoff will have to be released for flood protection and the smaller snowpack will reduce the amount available for release in spring and summer. A 3 C warming would reduce the area of the Sierra snowpack by 54%, and total unimpaired runoff through the estuary from April to July by 33% (California Energy Commission 1989).

# 4.2 Water Development

A continued trend with the potential to have great impacts on aquatic resources of the Delta and North Bay is further water development in the Central Valley. Possible developments include:

- 1. increased water storage on tributary streams which will reduce the amount of water entering the Delta and Bay or will further reduce seasonality of water flow patterns, as by construction of Auburn Dam or increasing the capacity of Shasta Dam;
- 2. more rapid transport of water through or around the Delta by deepening of channels or construction of facilities like the New Hope Cross Channel;
- 3. increased storage downstream, as with Los Vaqueros reservoir, to capture more winter and spring runoff;
- 4. establishment of temporary storage facilities within the Delta to provide a holding area for water to be released after river flows decline, as in the proposed Delta Wetlands project. Each of these types of development serves to give greater control of water through the Delta so that a larger and more constant supply of water is available for diversion. Thus, they share

effects that reduce seasonality and flow patterns in the estuary but each also has different subsidiary impacts on aquatic resources.

Secondary effects due to increased upstream storage will principally be their effect on migratory species. The increased prominence of the fall run chinook salmon relative to other salmon runs is partially an effect of the cool water discharges from Shasta Dam that provide appropriate temperatures for spawning below the dam during August and September. Further water development is likely to accelerate the declines of other runs. Similarly, the migration of first-time spawning American shad up tributary streams is largely triggered by the amounts of water entering the mainstem from the tributaries (Daniel 1989, cited in California Energy Commission 1989) and further damming or diversion on the tributary streams is apt to reduce their ability to sustain runs of American shad.

Land development, particularly dredging, diking and filling, have slowed in recent years and have doubtless already had their greatest impact on aquatic resources in the estuary during the massive landscape alterations that began in 1860.

## 4.3 Effects of likely future changes on aquatic resources

Based on the forgoing we expect the future of aquatic resources of San Francisco Bay and Delta to be most affected by four processes:

- 1. Increasing rates of diversion will reduce the amount of water flowing into the Bay. This will produce more frequent drought conditions in the Bay by making normal years have the outflows expected of dry years and dry years have the outflows of critical years. Even if diversion rates are held at current levels the amplification of the effects of occasional drought conditions is likely to produce further shifts in aquatic resources of the Bay and Delta. The drought of 1976-77 coincides with several major shifts in the abundance of aquatic resources and the drought of the late 1980s coincides with further sharp changes in the abundance and species composition of aquatic communities of the upper Bay.
- 2. Increasing global temperature will increase the amount of salt water entering the Bay, relative to freshwater. Total volume of water in the Bay will also increase and lead to unforeseeable changes in patterns of land use and reclamation. Increased sea level will also reduce the amount of freshwater which can be exported from the Delta by the mechanisms currently in place and will probably result in unpredictable changes in water export procedures.
- 3. Exotic species are likely to continue to invade the estuary. If habitats are changed by any of the projected trends it will increase the likelihood of success for some of the introduced species. The effects of the newly introduced copepods have begun to be understood in relation to other aquatic resources. The Asian clams have not been around long enough, particularly under wet year conditions, to estimate their impact on the future of the Bay. As in the past, it will be difficult to separate the effects of habitat alteration on the aquatic resources of the estuary from the effects of introduced species that are better able

to use the altered habitats. The species which will invade are impossible to predict but they are likely to continue to be species transported in ballast water.

## 4.4 Use of existing data to estimate effects of future trends

The drought of the last five years may have created conditions indicative of the permanent changes likely if San Francisco Bay changes toward a more ocean dominated system as a result of either global warming or decreased freshwater outflows. This assumption allows assessment of how each aquatic resource species responds to decreased outflows and increased marine intrusion but it cannot encompass the effects expected from increased wintertime storms. The aquatic community of the Bay has been intensively studied only since about 1980 and the first five years provide examples of the strong annual variations in outflow that have typified the Estuary for much of its recent history while the second five years have been drier than average for almost all months. Changes in the abundance of each species within each year show several clear shifts from the more normal conditions of the early 1980s to the prolonged drought of the latter 1980s. The fact that many of these trends are sharp and parallel for species that use similar parts of the estuary suggests that, although the data span only ten years, they are sufficient to identify the dominant trends in the system. These trends are the subject of most of the rest of this report.

## 5 Aquatic Habitats and Communities of the Estuary

## 5.1 Tributary streams

Most studies of aquatic resources have focussed on processes and species that occur within arbitrary boundaries which divide the estuary from the surrounding land. Runoff as a contribution to non-point sources of pollution has been recognized as one interconnection between the numerous small streams of the bay area and the bay itself. In Appendix A we describe the importance of outflow from such streams as contributions to the carbon budget of different parts of the bay. However, the role of these streams as repositories of aquatic resources of the bay has received little attention in recent years.

There are approximately 175 tributary streams in the Bay Area with approximately 60 creeks that flow directly into the Bay. Most streams have suffered, especially in their lower reaches, from habitat loss through channelization, removal of riparian vegetation, reduced water quality and the construction of barriers to fish migration (Leidy 1984). Some still support runs of steelhead (Oncorhynchus mykiss), coho salmon (O. kisutch) and chinook salmon (O. tshawytscha).

The abundance of native fish species in these streams generally reflects the intensity of urbanization of the surrounding lands (Aceituno et al. 1976; Scoppettone and Smith 1978; Leidy 1984; Leidy and Fiedler 1985). Leidy (1984) examined the distribution and abundance of fishes in these creeks in 1981. In North Bay streams, native species were dominant in 76% of the sampled sites and only 10% of the sampled sites were fishless. In streams of the east side of the Bay and north of Alameda Creek, 60% of the sites were dominated by native species. In South Bay streams only 42% of the sites were dominated by native fishes and 30% of the sample sites were fishless.

The fishes of the tributary streams of the Bay Area are particularly sensitive to habitat loss. Resident freshwater populations are isolated from each other by the salt water of the Bay. Hence, many of the native species are incapable of recolonizing a stream that loses its native fauna. The drought of 1976-1977 was suspected to be responsible for the disappearance of at least one native fish that had been recorded from Bay Area streams previously (Leidy 1984). The mouths of these creeks also provide numerous examples of estuarine conditions that are favored by some taxa. The tidewater goby (Eucyclogobius newberryi) is a species listed by the State Department of Fish and Game as threatened and was formerly found at the mouths of 10 of the 60 creeks flowing into the Bay; they are now extirpated from at least 9 of their former Bay locales (Moyle et al. 1989).

## 5.2 Salt ponds

Large areas of what was formerly tidal marsh habitat near South and San Pablo Bay have been transformed into salt ponds. Around San Pablo Bay these ponds comprise 36 sq. km.; South Bay salt ponds are about three times as extensive (111 sq. km.; Lonzarich 1989). These

ponds increase in salinity as the water evaporates, and consequently they harbor different arrays of species at different 'ages' of the ponds. As the ponds fill, several species of shallow habitats are commonly found, including topsmelt, threespine stickleback, longjaw mudsucker, staghorn sculpin, and rainwater killifish. At higher salinities the species list shortens until only topsmelt are left in the ponds of South Bay (Carpelan 1957) and threespine sticklebacks in the ponds near Napa.

The invertebrate fauna of these ponds shows a similar reduction in diversity through time. Recently filled ponds support dense populations of several worms, clams, snails, benthic crustaceans, and insects (Carpelan 1957; Lonzarich 1989). At the highest salinities only brine shrimp (Artemia salina), water boatmen (Trichocorixa reticulata), and water striders (Ephydra millbrae) are found.

These ponds are very important habitat for a number of waterfowl species (Harvey et al. 1988) but their aquatic populations are isolated from the other aquatic resources of the Bay. The status and trends of salt pond populations are, therefore, more thoroughly considered in the status and trend reports on wetland communities and on wildlife.

## 5.3 Plankton communities

## 5.3.1 South Bay

In almost all water bodies, trophic relationships on the microscopic level can be quite complicated. In addition to the classic pathway, in which energy passes from primary producer (e.g., phytoplankton) to a macroscopic consumer (e.g., copepod), a number of other pathways have become recognized over the past few decades. Although these alternative trophic links in the San Francisco Estuary have not been received much attention, they are almost certainly of importance. Some generalizations from studies in other estuaries are therefore in order. These microbial relationships are probably present throughout the Estuary.

In the water column, many kinds of organic matter are present. Although most of the living material in the Estuary's waters may be in the form of microalgae, large amounts of detritus—dead organic matter— are also present. Some of this material may have originated from extracellular products of photosynthesis or dead phytoplankton, but many other sources probably contribute as well (Appendix A). This detritus, depending on its form and size, may support higher organisms in several ways. In particulate form, some of it might be consumed directly by copepods, but much of it is probably processed by bacteria, which in turn may be consumed by protozoans. The work of Hollibaugh and Wong (pers. comm. 1991) has shown that this "microbial loop" is quite active in certain parts of the Estuary. Planktonic aerobic heterotrophs appear to form part of an important food web pathway in the San Francisco Estuary. Production at times rivals and even exceeds phytoplankton production, reflecting the presence of alternative energy sources such as riverine inputs of organic matter (Hollibaugh and Wong, pers. comm. 1991). Much of this production may be passed on to bacterivorous zooplankton and zoobenthos.

Some of the smaller algae are probably consumed by protozoans as well. Small flagellated algae such as the cryptomonads are common in almost all parts of the estuary. Tintinnids can serve as an important trophic link between small phytoplankton ( $<10~\mu m$  diameter) and metazoan zooplankton such as the estuarine copepod *Acartia* (Robertson 1983). As mentioned previously, *Tintinnopsis* can be common throughout the Bay and western Delta. Another ciliate, *Mesodinium rubrum*, achieved sufficiently high densities to discolor large areas of South Bay during spring and summer of certain years (Bain and Pintler 1966; Cloern 1984). Small flagellated protozoa are known to play a similar trophic role in many water bodies, but their significance in San Francisco Bay has not been delineated.

The presence of these microbial pathways is of the utmost importance. Each trophic link usually represents a substantial loss of energy to the system due to respiration. Unassimilated and excreted material has the opportunity to enter the food web again, but respiratory losses are a true sink. The proportion of production at one trophic level that is passed on to the next is highly variable, depending on the organisms and ecosystems in question, but it is not unusual to pass on only about  $25 \, ^{\circ}/_{\infty}$ . As a consequence, the interposition of an extra trophic link can be equivalent to a four-fold drop in organic matter sources at the base of the food web. It is therefore important to focus on the food web structure, as well as the supply of energy to the base of the food web. We are much further along with the latter issue (Appendix A) than the former. The lack of understanding of these microbial trophic relationships in the Estuary is a serious obstacle to our understanding of the ecosystem.

In San Francisco Bay, planktonic diatoms are usually the dominant algal form during spring blooms (Cloern 1984; Cole et al. 1986). In South Bay, dominant bloom species include Cyclotella spp., Thalassiosira spp., and Skeletonema costatum. Diatoms are often less abundant at other times of the year, when small flagellated algae may predominate. These include the cryptomonads Chroomonas and Cryptomonas, as well as the green alga Pyramimonas. In South Bay channels, bacterioplankton production can be a large fraction of phytoplankton production, although the ratio is much less in shoal areas. During winter-spring 1980, tintinnid protozoans -- mostly Tintinnopsis spp. and Eutintinnus neriticus -- constituted only a few percent of the zooplankton biomass (Ambler et al. 1985). Rotifer biomass, primarily Synchaeta sp. -- was less than 1% of the total. During summer-fall, protozoan and rotifer biomass was even less important. Limited experiments suggest that most of the bacterioplankton production is being grazed (Hollibaugh and Wong, pers. comm. 1991). As adult copepods cannot readily feed on isolated bacteria, either most of the production occurs on floating detrital particles, unidentified bacteriovores are present, or the contribution of these protozoans, rotifers, and copepod nauplii to secondary production is much higher than suggested by their biomass. The dominant copepods of South and Central Bay are Acartia spp. and Oithona davisae.

## 5.3.2 San Pablo Bay

Thalassiosira spp. were the major bloom taxa in San Pablo Bay in 1980 (Cole et al. 1986). Skeletonema costatum can also be a dominant. Various Cyclotella species dominated the post-bloom period, and Melosira spp., Fragilaria crotonensis, and Amphora spp. predominated before

the bloom. Unlike South Bay, small flagellated cryptomonad and green algae did not appear to be important. Protozoan and rotifer biomass were also less important than in South Bay, which may reflect the paucity of small algae. The diversity of both protozoans and rotifers increased, however. The tintinnid *Parafavella* and rotifer *Keratella* were observed in San Pablo channel samples, and the rotifer *Brachionus* in the Carquinez Strait channel. Bacterioplankton production also was a smaller proportion of phytoplankton production in San Pablo Bay, compared to South Bay, although still substantial (Hollibaugh and Wong, pers. comm. 1991). Larger zooplankton species include the copepods *Acartia* and *Eurytemora* in the dry and wet seasons respectively.

## 5.3.3 Suisun Bay

Suisun Bay phytoplankton blooms were dominated by Skeletonema costatum and Thalassiosira decipiens in 1980 (Cole et al. 1986). Melosira, Cyclotella, and unidentified green algae were important at other times of the year. Keratella sp. was the dominant rotifer and Tintinnopsis sp. the dominant protozoan. Both rotifers and protozoans appeared to be unimportant in terms of biomass. Bacterioplankton production was comparable to that of San Pablo Bay. Larger zooplankton include Eurytemora, which has been recently replaced by the introduced Pseudodiaptomus. In dry seasons Acartia usually invades and in wet seasons the upstream copepods Diaptomus and Cyclops, appear along with cladocerans such as Bosmina and Diaphanosoma.

### 5.3.4 Delta

Wintertime phytoplankton of the Delta are frequently dominated by cryptomonads (Ball 1975) or the diatom *Achnanthes* (California Department of Water Resources 1985). However, these wintertime populations are usually at low densities so the emphasis in the following discussion is on those species that dominate the productive period from spring to fall.

The distribution of species can be masked by their simultaneous growth periods. The 1984 peak in chlorophyll a (California Department of Water Resources 1985) showed a maximum in the south central Delta with a more rapid decline toward the west and north than toward the south, suggesting a single bloom. In fact, this bloom varied in species composition as much as in density (California Department of Water Resources 1985). In 1982 there was a similar situation (California Department of Water Resources 1983) when three, more-or-less simultaneous blooms were responsible for the high June concentrations of chlorophyll a throughout the Delta. Because of the formation of transition zones, five different algal communities constituted this bloom (California Department of Water Resources 1983). Small-scale discrepancies in timing of the peaks within these associations (California Department of Water Resources 1983) suggested that they were controlled by different environmental factors. The different growth rates of the different species responsible for these blooms may be one of the largest stumbling blocks in developing a predictive model of delta phytoplankton (Brown 1986; HydroQual 1984).

### 5.3.4.1 Western and Central Delta

In the western and central Delta, prior to 1976, phytoplankton blooms were dominated by Skeletonema potamos, Melosira granulata, Thalassiosira spp., or Cyclotella spp. (Ball 1987). In May of 1976, however, a bloom of Melosira granulata occurred. Since that time, almost all large blooms have been due to Melosira granulata. The small cryptomonad flagellate Rhodomonas lacustris is also widely distributed throughout much of the Delta.

#### 5.3.4.2 Northern Delta

The northern Delta is dominated by the waters of the Sacramento River and associated Yolo Bypass and supports the lowest phytoplankton concentrations of the area. As described above, water from the Sacramento River enters the Delta carrying chlorophyll a at concentrations seldom greater than  $6 \mu g/L$  in the summer. During the winter, when water residence times, insolation, and temperature are least, chlorophyll a concentrations are frequently as low as  $1 \mu g/L$ . As the water flows through the Delta to Green's Landing these concentrations are generally doubled. The low flows during the drought generated phytoplankton concentrations several times greater than these. High-flow years can prevent any measurable phytoplankton growth.

This area, like most of the Delta, is dominated by diatoms (Bacillariophycae) but flagellates are occasionally abundant. Abundances peak in the spring, although in 1984 there was a wintertime peak because of *Asterionella* in January and *Cyclotella* in February. From 1969 to 1974 the dominant phytoplankton were *Thalassiosira*, *Cyclotella*, and *Melosira* (Ball 1977, Ball and Arthur 1979).

### 5.3.4.3 Southern Delta

The southern Delta is dominated by waters of the San Joaquin River. The San Joaquin is generally shallower, warmer, slower-flowing, and more nutrient-rich than the Sacramento and, so, has supported much greater concentrations of phytoplankton. Peak plankton abundances in the south Delta are regularly 10 times as dense as those in the rest of the Delta. Because of the recirculation of agricultural water through the San Joaquin Valley, the south Delta has higher conductivities than most of the rest of the Delta. In fact, conductivities here are often similar to the saline areas of the western Delta. In consequence the algal community is frequently more similar in these two areas than in the rest of the Delta. The algal community from 1969 to 1974 was dominated by *Thalassiosira*, *Cyclotella*, *Stephanodiscus* (=Skeletonema?), and *Melosira*. The 1984 community was similar, but at times *Chlamydomonas* was abundant while *Skeletonema* was not reported.

Zooplankton of the Delta are moved around with the water so the animals from one river may often be found in the channels of another, leading to little distinctiveness in the plankton communities in any one area. The dominant zooplankton include the freshwater rotifers,

particularly Keratella, the cladocerans Bosmina and Daphnia, and the copepod Cyclops. The introduced Sinocalanus also occurs in abundance.

## 5.4 Fish distribution patterns

The Aquatic Habitat Institute has developed a segmentation scheme for the Sacramento-San Joaquin Estuary to reflect regions with distinct hydrodynamic characteristics. This segmentation scheme is designed to be particularly useful for tracking the effective areas of sewage outfalls and other physically dispersing materials (Gunther 1987). Unfortunately, the only sampling program with stations that are numerous and widespread enough to permit comparison with the AHI segmentation scheme is the CDF&G Bay Study (Figure 16). Thus, phytoplankton, benthos, epibenthos, and zooplankton can only be described, if at all, in broad geographical units, as in the preceding section. The degree to which the segmentation scheme corresponds to the distribution of fish is discussed below.

In this section we describe the distribution of fish species in the estuary to show how fish distributions are affected by season and by many of the physical features associated with hydrodynamics. Data are from the Interagency Ecological Program/San Francisco Bay Study (hereafter 'Bay Study'). This program has sampled with a variety of gear on a monthly basis throughout the Bay from January 1980 to the present. For this analysis we use the data through December 1988 for the 35 stations that were sampled on all sampling periods. We make no effort to analyze the distribution of species in relation to the measured salinity or temperature at each station for the Bay Study. These data are being analyzed by CDF&G and should appear shortly. We rely on the distance from the Golden Gate as a rough estimate of the mean salinity at each station and separate the data into quarterly groups to compare the degree to which species vary in their occurrence at a site in response to seasonal variability. Salinity, river outflow and temperature doubtless affect the distribution of fish in the Bay but the purpose of this section is to identify those fishes which are most often found at each site.

The most abundant species in the midwater and otter trawls at each station for each quarter in the sampling of the Bay Study are described in Appendix B. Stations are identified by their place in the segmentation scheme of Gunther (1987). The species which were caught in more than one third of the trawls made at a station are included, up to six, to give a profile of the types of fish found in an area. The total number of species (spp.) is reported as an estimate of species richness. The total catch (catch) for the station over all nine years for all species in each quarter is given as an estimate of relative fish abundance in each quarter (these data can only provide a very rough estimate of fish abundance across stations because the efficiency of the sampling gear varies with depth, substrate etc.). Because northern anchovy comprise about 80% of the fishes in the bay the total catch is given for all species except anchovy and the total with anchovy.

Analyzing the distribution of fish within each embayment to determine areas lacking common species can be as informative as noting the presence of species. Presence in one third of the trawls performed at each station over the nine years may under-represent rarer or less

easily caught species. No replicate trawls were performed to examine consistency of catch within one station at one time. These biases make the descriptions of the species characteristic of each site and season conservative in that other species may also occur consistently but are sampled less efficiently or consistently. Comparison of the total number of species (spp.) to the number which occur in the table gives a simple estimate of the predictability of catch at each site.

We attempt to describe the status of aquatic resources by looking at the consistency of their distribution in space and by season. The occurrence in at least a third of the trawls at each site will include species that were present for all months of a quarter for all years, those that were present in all months of the quarter for only three of the nine years of sampling, and those which were caught in only one month of the quarter but in each of the nine years. The description of trends through time is examined in a later section.



Figure 16 Sampling sites (in bold) of the CDF&G Bay Study and corresponding segments of the Bay

## South Bay Segments

#### Characteristics

The ship channel passes through the sampled area of South Bay. Broad shallows south of Hunter's Point are the dominant feature of the west side. The west side receives cooling water discharges from power plants at Hunter's Point. The eastern side is dominated by the port of Oakland and by shallow areas with some beds of eelgrass. At the upper end of the region a shallow area (San Bruno Shoal) separates the deep stations of Central Bay from other stations of South Bay. Coyote Creek and San Francisquito Creek are two of the streams carrying freshwater into South Bay.

The most frequently caught species in South Bay are shown in Table 2.

Table 2. Ranks (and number of occurrence) for the six most frequently caught fish species in the 1062 pairs of midwater and otter trawls performed at ten stations in South Bay.

Species	Rank in total midwater catch	Rank in Otter trawl
41		1 (550)
northern anchovy	1 (733)	1 (559)
jacksmelt	2 (475)	
Pacific herring	3 (407)	
shiner perch	4 (262)	2 (546)
topsmelt	5 (191)	
longfin smelt	6 (123)	
bay goby		3 (353)
white croaker		4 (321)
English sole		5 (336)
speckled sanddab		6 (269)

#### Channel sites

Five stations in South Bay sample three of the channel segments, station 101 in the southernmost area below the San Mateo Bridge (segment SB4), stations 107 and 108 in the channel from San Mateo Bridge to Hunter's Point (segment SB7) and stations 109 and 110 in the channel between Hunter's Point and Central Bay (segment SB10). Depths recorded at the channel station range from 12.6 m to 17.3 m.

#### Shoal sites

On the east side of South Bay, station 102 is over the mudflats between the Dumbarton and San Mateo Bridges (segment SB5), depths during sampling averaged 3.8 m. Stations 104 and 105 are in the shallows between the San Mateo Bridge and Alameda (segment SB8), depths

averaged 3.3 - 3.6 m. Stations 103 and 106 are over the San Bruno Shoals (segment SB6), depths during sampling average 3.3 - 3.6 m.

General patterns: fishes of South Bay

The fishes of South Bay are generally either species which are characteristic of California coastal lagoon type estuaries or more truly marine species that invade seasonally. The assemblage is dominated by northern anchovy, Pacific herring, shiner perch, jacksmelt and topsmelt, but their is little predictability in the species composition at many sites.

Two physical features appear to be associated with the consistent distribution of fishes within South Bay, depth and distance to Central Bay. Northern anchovy and Pacific herring are found in the midwater trawl at all stations but jacksmelt and topsmelt are caught only in the midwater trawl and usually in shallow stations, as is walleye surfperch. Shiner perch, on the other hand appeared more regularly in the midwater trawls of channel sites. In the otter trawl brown smoothhounds and brown rockfish only occur regularly in channel stations, although brown rockfish are only found regularly at one station, so it is impossible to say which environmental feature to which they are responding. Proximity to Central Bay seems to be the main determinant of the catch of brown rockfish and leopard sharks.

In the midwater trawls, the channel stations show a pattern of greater consistency in catch at the stations at either end of South Bay than at stations 107 and 108 in the middle. Despite large fluctuations in their abundance as they move in and out of the Bay on a seasonal basis, northern anchovy are one of the most consistent fish in the midwater catch at all South Bay stations. Pacific herring are found year round at the stations near Central Bay but are consistently present in more southerly stations only during the first six months of the year. Jacksmelt are collected regularly only in the midwater net and consistently at any one site only during the period from April to September. The midwater trawls at several stations catch longfin smelt regularly from January through March, except for the southernmost station (101) where they continue to be a regular part of the catch into the spring.

In the otter trawl catches, northern anchovies are among the most regular part of the catch at almost all stations and seasons. However they are a much smaller part of the catch and their numbers do not show the strong seasonality of the midwater trawl catch. At all stations predictability of catch is least in the months from October to December. As with the midwater trawl, station 108 yields a much less predictable catch than the stations to the north or south. Closer to Central Bay, white croaker is commonly caught in all seasons of the year, but at the southern stations they are less dependably present in the winter. Bay goby are caught for a larger portion of the year in channel sites and generally in the spring at shallow sites.

Midwater trawls at shoal stations are very similar to those of channel stations with two exceptions: jacksmelt are caught regularly year-round (or for at least three seasons) at several shoal stations, and walleye surfperch are regularly caught at station 106 off Hunter's Point and at station 104 near San Leandro.

Otter trawls at shoal stations yield fish associations that do not differ greatly from one side of the Bay to the other, but which are very different from the otter trawls performed in the channel. The fish assemblage of the shoal stations is much less predictable than that of the channel, with the period of greatest predictability limited to the months from April to June, except off Hunter's Point where the assemblage persists into the summer. The distribution of English sole also differs between the shoals and shallows. In the channel English sole are regular features of the catch for most of the year at station 110, near Central Bay, but they are not part of the regular assemblage at most of the other channel sites. At all shoal sites, however, English sole are always a regular part of the April-June assemblage.

The abundance and regularity of fishes at San Bruno Shoal is similar to the increased productivity of this area for phytoplankton and zooplankton (Appendix A).

## Central Bay

Most of Central Bay (segments CB11, CB3, and CB2) provides little shallow habitat so that the habitat is less heterogenous than in other embayments. Segment CB11 is one of the few areas in San Francisco Bay supporting eelgrass beds. Stations range in average depth from 10 to 24 m. Stations 211 and 212 are located in segment CB7, the shallow areas near the Berkeley mudflats, and have mean depths of 7.7 and 3.3 m, respectively.

The most frequently caught species in Central Bay are shown in Table 3.

Table 3. Ranks (and number of occurrence) for the six most frequently caught fish species in the 638 pairs of midwater and otter trawls performed at six stations in South Bay.

Species	Rank in midwater catch	Rank in Otter trawl
northern anchovy	1 (393)	2 (336)
Pacific herring	2 (335)	
jacksmelt	3 (211)	
longfin smelt	4 (154)	
shiner perch	5 (134)	1 (358)
white croaker	6 (113)	4 (331)
longfin smelt		6 (311)
speckled sanddab		5 (313)
English sole		3 (336)

General patterns: fishes of Central Bay

The dominant species of Central Bay are largely the same as those of South Bay, with increasing abundance of euryhaline species found in greater abundance in San Pablo Bay. The seasonal presence of chinook salmon distinguish Central Bay from South Bay. Speckled sanddab are present in higher abundances and for more of the year than in other embayments.

The main feature associated with the regular species composition at sites in Central Bay proximity of San Pablo Bay or the Golden Gate; sites closer to San Pablo Bay regularly yield fish characteristic of that embayment while sites closer to the ocean yield collections with more marine species. Only one truly shallow site is sampled so it is impossible to separate the effects of depth from location. However, it appears that catch in the shoals varies seasonally more than in the channel where the same set of species predominate for most of the year. Starry flounder were a species which uniquely characterized the shallow station.

The midwater trawl is characterized in Central Bay by two species, chinook salmon and topsmelt. The seasonal catch of chinook salmon at all deep water sites between the months of April and June, with occasional catches on an irregular basis in the months from July to September, separates all Central Bay stations from all South Bay stations. Chinook salmon smolt were absent at all stations during the rest of the year. Less obviously characterizing Central Bay is the consistent regular catch of jacksmelt without topsmelt. At most stations in South Bay jacksmelt outnumber and are more frequent in their occurrence than topsmelt but

stations where jacksmelt were regular were also often associated with regular catches of topsmelt. The two species appear to school together but topsmelt seem to be much less common outside of South Bay.

The deeper water fish assemblage sampled by the otter trawl reflects an abundant and diverse fish assemblage. The dominant species (English sole, shiner perch, white croaker, speckled sanddab and longfin smelt) are common for most of the year, with seasonal incursions by bay goby and plainfin midshipmen. At the more northerly stations longfin smelt rise in abundance and in frequency of occurrence.

## San Pablo Bay

San Pablo Bay provides extensive shallow habitat so that the habitat is very different than Central Bay. Four stations (323, 322, 321, 320 are arrayed in an arc across the broad shallows in the triangle formed by Point San Pedro, Tubbs Island and Mare Island in segment SP3. South of the channel the shoals are divided into segment SP5 west of Pinole Point, where station 317 is located, and segment SP6 east of Pinole Point which contains stations 318 and 319. Only station 325 is situated in the channel where mean depths were 11 m. (segment SP4), so it is not possible to identify the fish assemblage of deeper waters. All other stations are in the extensive shallows with mean depths less than 4.5 m.

The most frequently caught species in San Pablo Bay are shown in Table 4.

Table 4. Ranks (and number of occurrences) for the six most frequently caught fish species in the 852 pairs of midwater and otter trawls performed at eight stations in San Pablo Bay.

Species	Rank in total midwater catch	Rank in Otter trawl catch 2 (398)
northern anchovy	1 (539)	1 (417)
longfin smelt	2 (335)	- (, /
jacksmelt	3 (302)	
Pacific herring	4 (300)	6 (293)
striped bass	5 (207)	,
American shad	6 (155)	5 (313)
starry flounder	,	4 (321)
shiner perch		3 (336)
yellowfin goby		•

General patterns: fishes of San Pablo Bay

The fishes of San Pablo Bay consist of a resident set of estuarine species (longfin smelt, starry flounder, striped bass, and staghorn sculpin) and a set of more lagoon or marine species which invade in dry years or during the spring and summer months (white croaker, bay goby, jacksmelt, shiner perch). The embayment is also a regular home for the young of some species including English sole, Pacific herring and white croaker.

The main feature affecting the distribution of fish within San Pablo Bay seems to be primarily the distance to the Golden Gate. As the stations progress upstream their fish assemblage more often contains estuarine species and less often contains oceanic species. Only one deep station is sampled but its fauna appears to resemble that of the deep stations in Central Bay, noticeably in the regular seasonal presence of chinook salmon smolts, which are not regularly caught anywhere else within San Pablo Bay. Species of South Bay and Central Bay appear to invade San Pablo Bay either seasonally in the months when there is usually little freshwater outflow or occasionally in other parts of the year, when conditions are suitable. These invasive or seasonal species are principally jacksmelt, shiner perch, Pacific herring, bay goby and white croaker. American shad are caught at most stations but only in the period from October to December.

There seems to be more similarity between the stations at similar distances upstream than between stations on one side of the channel. Thus, stations 317 and 323 at the south end of San Pablo Bay are more similar to each other than to upstream stations on the same side. The same pattern is shown by stations 319 and 320 which are on the opposite sides of the channel at the north end of the bay.

Fishes particularly characteristic of San Pablo Bay include longfin smelt, which is captured regularly year-round here but is seasonal or scattered in its occurrence in South and Central Bay. Longfin smelt are also found more often in the otter trawl in downstream stations but is regularly caught in the midwater trawl here. Striped bass, staghorn sculpin and starry flounder are other species found regularly in most of San Pablo Bay in most seasons of the year. These species are all rarely encountered consistently at downstream sites.

### Suisun Bay

Suisun Bay provides both extensive shallow habitat and a long, deep channel that is thoroughly sampled by the Bay Study. Like South Bay, then, it is possible to examine patterns of different habitat use by species. The long channel runs close to shore on the southern side of the embayment so that almost all shallow habitat is on the north side. Channel stations (428, 429, 432, 433) are all in segment SU1 with average depths of 8 to 10 m. Shallow stations 430 and 431 are in Grizzly Bay (segment SU2) which is adjacent to Suisun Marsh (SU4). Honker Bay (segment SU3) is a smaller shallow embayment upstream and contains station 534.

The most frequently caught species in Suisun Bay are shown in Table 5.

Table 5. Ranks (and number of occurrence) for the six most frequently caught fish species in the 747 pairs of midwater and otter trawls performed at seven stations in Suisun Bay.

Species	Rank in total midwater catch	Rank in Otter trawl catch
·		1 (671)
striped bass	1 (729)	2 (516)
longfin smelt	2 (682)	6 (149)
northern anchovy	3 (345)	
American shad	4 (323)	
Delta smelt	5 (262)	3 (364)
yellowfin goby	6 (181)	4 (332)
starry flounder		5 (321)
staghorn sculpin		

General patterns: fishes of Suisun Bay

Carquinez Straits appear to represent a major break in the distribution of species within the estuary. Several of the regular species of Suisun Bay are absent from downstream sites, some are common in San Pablo Bay and more common in Suisun Bay and a number of the common species of the lower bays are absent from Suisun Bay. Delta smelt and Sacramento splittail are regularly caught in Suisun Bay but are very rarely found downstream. The six-species assemblage (striped bass, yellowfin goby, longfin smelt, starry flounder, staghorn sculpin, and Delta smelt) found in the trawls near Grizzly Bay is a consistent and unique feature of this bay. The regular catch of white sturgeon makes Honker Bay unique. The greatly reduced abundance of northern anchovy and Pacific herring and the near absence of jacksmelt, white croaker, and bay goby are also distinctive features of Suisun Bay catches.

Midwater trawls throughout Suisun Bay are most likely to contain striped bass and longfin smelt, other species are seasonally present but in general the number of species encountered is small and the species composition of a catch is unpredictable.

Otter trawl catches, on the other hand are quite predictable, and the species groups conform well to the segmentation scheme of Gunther (1987). In the deep channel (SU1) the catches are unpredictable, in Grizzly Bay (SU2) the catches are larger and the species composition is highly consistent throughout the year. In Honker Bay (SU3) the catch is very small and very few species can be expected.

#### Western Delta

Three stations (535, 736, and 837) are on the border of the San Francisco Bay complex and the western Delta. Station 535 is below the confluence of the two rivers at Chipp's Island, station 736 is in the lower reaches of the Sacramento River and station 837 is in the lower reaches of the San Joaquin River. Water moves among these stations, not only by river flow, but twice daily water moves up both river channels on the rising tides and, depending on outflow and diversion rates, there is a net movement of water up the lower San Joaquin from either of the other two stations.

Conditions at each site present very different environmental conditions for the fishes. At 535 the water is often a mix of Sacramento River water and salt water. At station 736 the water is predominately Sacramento River water with 2limited movement of mixed water into the station on high tides. Station 837 may have any combination of San Joaquin River water, Sacramento River water flowing around Sherman Island and up the San Joaquin River, or a mixture of water moving back and forth with the tides. Depths also distinguish the three stations because 535 and 736 are over 10 m. deep whereas station 837 is only 4.4 m deep on average.

The most abundant species from each site are given in Table 6.

Table 6. Ranks (and frequency of occurrence) for the six most abundant species fish species in the 214 pairs of midwater and otter trawls of the CDF&G Bay Study at stations east of Suisun Bay.

San Joaquin midwater	otter	Sacramento midwater	otter
2 (41)	1 (87)	1 (65)	1 (49)
1 (49)		3 (26)	2 (28)
4 (23)	3 (10)	4 (34)	5 (19)
5 (23)	3 (10)	6 (17)	3 (1))
6 (3)			
	2 (36)		3 (30)
	4 (12)		6 (22) 4 (13)
	5 (15)		(13)
	midwater  2 (41) 1 (49) 4 (23) 5 (23) 3 (26)	midwater otter  2 (41)	midwater otter midwater  2 (41)

General patterns: comparisons across embayments

Some species are characteristic of each embayment (Figure 17). Carquinez straits, with its high velocities and diverse conditions of salinity and temperature appears to be a barrier for many fish species. Several abundant species occur in abundance only on one side or the other. Downstream of Carquinez Straits most species can be found occasionally anywhere, but most species also show a regular pattern of occurrence within one or two embayments or within a particular season.

South Bay is the only embayment where topsmelt and brown smoothhounds are regularly found at particular stations. Chinook salmon and American shad do not occur regularly anywhere in South Bay but are dependable components of all upstream embayments. Bay gobies are found for most of the year at some sites in South Bay but are more seasonal in their occurrence in Central and San Pablo Bay and are never found regularly at any site in Suisun Bay.

Central Bay is characterized by a very rich assortment of species in the otter trawl, entering from the lagoon-like South Bay, from the more freshwater regions of San Pablo Bay and from the ocean. Speckled sanddab is more abundant, and occurs more frequently and more regularly in Central Bay than in other embayments. English sole and starry flounder appear to prefer stations of different depth, with starry flounder found regularly only in shallow sites in Central Bay. Anadromous species must, of course, pass through Central Bay but only chinook salmon smolts are regularly caught at the sampling sites.

San Pablo Bay catches reflect a characteristic assemblage of euryhaline species which is seasonally invaded by lagoon species from South Bay and marine species. The year-round assemblage consists principally of longfin smelt, starry flounder, striped bass, and staghorn sculpin. Regular invaders in the spring and summer months from downstream include jacksmelt, white croaker, bay goby and shiner perch. San Pablo Bay is also used as nursery grounds for English sole and Pacific herring (as well as Dungeness crab). Anadromous species must pass through, including American shad and chinook salmon. American shad are found in the shallow of the north side of the embayment whereas salmon are usually taken at the channel site. The absence of American shad from Central Bay is probably a reflection of the absence of any sampling site in the shallows around Richardson Bay or Paradise Cove.

Suisun Bay supports the most distinctive fish assemblage. Striped bass, longfin smelt, Delta smelt, starry flounder, yellowfin goby, and staghorn sculpin are a consistent set of species in the shallows of Suisun and Grizzly Bay. Unlike South Bay the channel stations are much less predictable than the shallow stations. White sturgeon, Delta smelt and splittail are not caught consistently downstream. Jacksmelt, English sole and bay goby are three species that are abundant downstream but occur very rarely in Suisun Bay.

The western Delta stations support very few species and very few individuals compared to most downstream stations. The San Joaquin River station, probably due to stresses caused by the diversity of kinds of water that regularly flow through it, supports very few species. In the midwater trawl only migratory species consistently occur in the catch, except for threadfin shad which are probably washed out from above. The regular catch of bigscale logperch in the otter trawl makes this station distinctive. The Sacramento River station also yields only migratory

species in the midwater trawl, but they generally occur in larger numbers and more consistently than the San Joaquin River station. White catfish are regularly caught only at this site.

Overall, the pattern of species diversity and consistency shows a lower Bay which is regularly occupied by many species that move around seasonally along the channels. Some move into shallow stations while others remain in the channel. Fish that move into or through the Bay to spawn or whose young enter the bay from ocean spawners include plainfin midshipmen, English sole, Pacific herring, American shad, and chinook salmon. Occasional invaders of the bay that optionally spawn in the bay include white croaker, brown rockfish, brown smoothhound. Fishes of the coastal region and lagoons that concentrate in the South Bay but move into other embayments when salinities stabilize in spring and summer include jacksmelt and bay goby and, to a much smaller extent, topsmelt. The fluctuating salinities of the upper bay and western Delta, and the narrowness of Carquinez Straits greatly reduce the diversity of species but the species which can deal with fluctuating salinities comprise a consistent assemblage that shows little seasonality aside from movements to spawn.

Ignoring seasonal differences and different distributions at different depths still permits identification of characteristic groups of species in each embayment (Figure 17).

# Most Frequent Species in Otter Trawls

northern anchovy staghorn sculpin longfin smelt bay goby English sole shiner perch white croaker speckled sanddab brown smoothhound plainfin midshipman	starry flounder	yellowfin goby – striped bass –	— white sturgeon — delta smelt — Sacramento splittai — nan white catfish
Plaining Thiashiphian	Tacine Henrig	plainin madrip	
northern anchovy longfin smelt	equent Species		
Pacific herring jacksmelt shiner perch			delta smelt yellowfin goby Sacramento splittali
plainfin midshipman		<ul> <li>striped bass</li> </ul>	
topsmelt bat ray walleye surfperch bay goby	chinook salmon American shad white croaker Pacific pompan		white sturgeon
South	Central	San Pablo	Sulsun

Figure 17 Ten most frequently captured species in each embayment 1980-1988; data from CDF&G Bay Study.

### 6 Trends in Aquatic Resources and Possible Causes

### 6.1 Trends in organic carbon sources (see Appendix A for details)

### 6.1.1 South Bay

For the channel of South Bay during the period 1980-1987 there was no apparent trend in annual production. (Cloern 1990; Figure A.4 in Appendix A). Peak productivity varied markedly from one year to the next but fluctuations in annual production were small.

Major decreases in tidal marsh did take place between 1850 and 1958 (Atwater et al. 1979), and tidal plants could have been a major organic carbon source in the nineteenth and early twentieth century. However, comparison of maps for 1958 and 1985 show a decrease of only about 1% in mudflat area and 10% in tidal marsh area during that period. Therefore, there is no evidence to suggest recent significant decreases in either benthic microalgal productivity or tidal marsh export of organic carbon.

Point source discharge is the only source with a detailed record for the years prior to 1980. The decrease has been quite remarkable (Appendix A, Fig. A.5), particularly since 1972 when the Federal Clean Water Act required a minimum of secondary treatment for all dischargers. The peak in organic carbon from this source in 1965 was almost exactly 10 times that in 1985. In view of the interannual variability in phytoplankton productivity, municipal wastewater could have been one of the dominant organic carbon sources for the South Bay during the 1960s and early 1970s, at least for years when microalgal activity was low. It is clear that point source discharge no longer plays a large role in the organic carbon supply for South Bay.

Regions in South Bay which receive higher sewage loads per unit area may show greater importance of point source discharges of carbon, either now or in the past. However, separate estimates for phytoplankton productivity and other processes in these zones are not available for comparison.

## 6.1.1.1 Causes of trends in South Bay productivity

Assuming that the South Bay food web is now driven primarily by energy from phytoplankton and, perhaps, benthic microalgae, the controls on year-to-year fluctuations in primary productivity are of great interest. Nutrient concentrations typically exceed levels that limit phytoplankton growth rates and are thus not a factor (Conomos et al. 1979). In the absence of nutrient limitation, productivity can be shown to depend on three variables: surface irradiance, the proportion of the water column in the photic zone, and phytoplankton biomass. This is also true of many other estuaries (Cole and Cloern 1984; Cole and Cloern 1987; Cloern 1987).

Cloern (1979, 1982, 1984) and Cloern et al. (1985) hypothesized a mechanism contributing to interannual variability in South Bay based on the depth of the photic zone and phytoplankton biomass. When periods of high Delta discharge in winter-spring coincide with periods of low tidal current speed during the tidal cycle, South Bay waters stratify. The mixed layer becomes smaller, and more of the phytoplankton are held higher in the water column. In addition, heavier suspended particles sink out of the stable surface layer and turbidity decreases, resulting in a deeper photic depth. The result is an increase in the growth rate in the mixed layer.

Phytoplankton in the mixed layer also become effectively isolated from benthic mollusks, polychaetes, and other suspension feeders, which are capable of filtering the entire water column daily. Phytoplankton biomass is thus allowed to rapidly increase.

If this mechanism is an important source of interannual variability, there should be a relationship between annual phytoplankton productivity in South Bay and Delta discharge. Cloern (1990) provided evidence for this relationship using estimates of net photic zone productivity in the channel for the period 1980-1987. The linear relationship between discharge and productivity accounted for 65% of the variability. The statistical evidence supports the hypothesis that river discharge contributes to interannual variability of phytoplankton productivity in South Bay. It should be noted, however, that the effects of river outflow are heavily damped and that variability in annual production in South Bay channels varies only by a factor of two.

However, about half of South Bay may be too shallow for this stratification mechanism to operate and over 60% of the annual phytoplankton production takes place in these shoal areas. In addition to Delta-derived intrusions of turbid water, local streams, runoff and resuspension of sediments (Conomos et al. 1979) may play a role in reducing productivity in shallower waters on a seasonal basis. Resuspension of chlorophyll (Thompson et al. 1981) also may contribute to variability in algal biomass.

The recent appearance of the Asian corbulid clam *Potamocorbula amurensis* (Carlton 1990) introduces a new element of uncertainty, particularly for South Bay south of the Dumbarton Bridge. Potamocorbula is currently present, but not abundant, in South Bay both north and south of the Bridge (Carleton 1990). According to a synoptic survey in 1973 (Nichols 1979; Thompson and Nichols 1981), benthic invertebrate biomass south of the Bridge was 50% less than biomass north of the Bridge in summer, 80% less in winter. Organic carbon sources have not yet been tallied for the lower South Bay independently. Little reason exists, however, for expecting a lower food supply, particularly as tidal marsh export, point source discharge, and runoff are probably much higher here than for South Bay as a whole. A potential may be present for higher benthic biomass, increased grazing pressure, lower phytoplankton biomass, and reduced phytoplankton productivity. Potamocorbula perhaps can exploit this opportunity because of its apparent ability to withstand a much wider range of sediment types and salinity than other benthic macroinvertebrates (Carleton 1990). In South Bay north of the Dumbarton Bridge, on the other hand, benthic biomass is more typical of intertidal communities (e.g., Knox 1986b). Potamocorbula may very well displace certain members of the current estuarine invertebrate community, but the total biomass and consequent grazing pressure may not change dramatically. Note that interannual variability is high among the benthos, despite the absence of long-term trends (Nichols and Thompson 1985b); thus, the applicability of the 1973 data to subsequent years is actually unknown and the suggestions made here highly speculative.

#### 6.2 Central Bay

No long-term chlorophyll series exist to adequately characterize interannual variability of either phytoplankton or benthic microalgae in Central Bay. Although wastewater discharge must have been a significant source of organic carbon in the recent past, point source discharges no longer appear to play an important role in the carbon budget of Central Bay. Based on the movements of materials through Central Bay from adjoining subembayments and the coastal ocean, Central Bay can be expected to show different patterns than each of the neighboring

areas. The different natures and causes of interannual variability in each embayment make the patterns in Central Bay particularly difficult to predict or analyze.

### 6.3 San Pablo Bay

As in Central Bay, interannual variability of phytoplankton activity is difficult to characterize and to understand because of the paucity of long-term chlorophyll or productivity measurements in San Pablo Bay. During 1971-1973, chlorophyll samples were collected from both shoal and channel sites, but routine sampling has since been confined to channel sites. It is particularly unfortunate that no long-term data series are available for the shoals, as most annual phytoplankton production probably takes place in the shallower region. Based on the study of seasonality during 1980 (Cloern et al. 1985) and the chlorophyll data that do exist for San Pablo Bay (Ball 1987a), interannual variability of phytoplankton has been attributed to processes similar to those of Suisun Bay. Point source discharges have never been important, even at their peak in 1970 (see Appendix A).

### 6.4 Suisun Bay

As discussed in Appendix A, transport of chlorophyll into Suisun Bay was strongly related to flow and this transport of riverine carbon may account for most of the available material at the base of the food chain in Suisun Bay. Year-to-year fluctuations in riverine loading largely reflect the corresponding variability in Delta outflow. The current drought period that began in 1987, in particular, is probably a time of highly reduced chlorophyll loading from Delta outflow.

Part of the organic material carried into Suisun Bay can be attributed to upstream point source dischargers. Through the 1970s, the amount of this material declined by more than 75% (Hansen 1982). The significance of the decrease during the 1970s is uncertain. The measurements of biological oxygen demand in the water at Chipp's Island show no trend through the same period; this suggests that upstream changes in municipal wastewater discharge did not affect the concentrations of organic material in Suisun Bay. The evidence is not conclusive, however, as the Chipps Island station is subject to influences from within Suisun Bay as well as from Delta discharge.

Comparing primary productivity measures in 1988, a "very dry" year, with the data of 1980, an "intermediate" year, shows that productivity during 1988 was much lower than in 1980. Photic zone productivity fell by a factor of five at shoal and channel stations. This decreased productivity was due to lower phytoplankton biomass, not lower growth rates.

Phytoplankton productivity in Suisun Bay -- even more so than for the other embayments -- is overwhelmingly dominated by shoal productivity. Interannual variability in productivity must therefore reflect fluctuations in shoal, not channel, productivity. The decrease in productivity between 1980 and 1988 was largely attributable to biomass changes, and not to a change in photic depth (which actually increased in 1988). If biomass is generally the controlling factor for productivity in Suisun Bay, it follows that shoal biomass fluctuations should be a guide to variability in embayment productivity. Long-term data for chlorophyll a at shoal stations in

Grizzly Bay and Honker Bay suggest that phytoplankton productivity in Suisun Bay has been depressed since 1982-1983. Productivity in 1977 also appeared to be low.

As in San Pablo Bay, recent trends for tidal marsh area cannot be evaluated. Point sources, when they were four times higher in 1970 (Fig. A.5), may sometimes have been as significant as phytoplankton or tidal marsh sources, but even then they would have been secondary to loading from Delta discharge.

### 6.5 Causes of trends in productivity in San Pablo and Suisun Bays

Contributions of organic material from Delta discharge depends on the volume of discharge and on the riverine concentrations of organic materials. Despite large-scale changes in the abundance and composition of riverine phytoplankton (see Ball 1987a,b for a detailed analysis), annual chlorophyll concentrations in recent years appear to be largely proportional to annual Delta discharge. Variability in river-borne phytoplankton is evidently inadequate to mask the effects of flow volume.

Phytoplankton productivity in Suisun Bay and San Pablo Bays is controlled by shoal phytoplankton biomass. Two processes control interannual variability. The first is the effect of Delta outflow on the residence time for phytoplankton biomass. Much of the work on phytoplankton activity within the northern reach of San Francisco Bay has focused on the significance of the entrapment zone resulting from estuarine circulation (Peterson 1975). Net water column productivity is almost always negative in the channel because of the small portion of the water column in the photic zone, so biomass must be imported for accumulation to take place. During periods of high Delta outflow, an entrapment zone forms in the channel of San Pablo Bay which increases the residence time of algae dispersed from shoals by tidal mixing and allows such biomass accumulation. As flows decrease, the entrapment zone moves into Suisun Bay where it performs a similar function. During particularly low flows, the entrapment zone is located in the western Delta. Arthur (1975) first hypothesized that positioning of the entrapment zone relative to large expanses of shoal area was the most critical factor regulating accumulation of phytoplankton in the zone. Further work has largely borne out this contention (Arthur and Ball 1979, 1980; Ball 1977, 1979; Cloern et al. 1983, 1985; Catts et al. 1985; Ball 1987a).

The spatial distribution of primary productivity need not reflect that of biomass. When an entrapment zone is present, the residence time for certain phytoplankton and detrital particles is increased and physical transport losses are smaller. Perhaps even more important, the concentration of food particles permits more efficient feeding by planktivores in the zone. Nonetheless, in the deeper river channels, the zone may still be an area of reduced or even negative primary productivity because a high proportion of the water is out of the photic zone. For the entrapment zone to stimulate primary productivity, shoal residence time must be increased: by decreasing the gradient of biomass between shoal and channel, the entrapment zone probably suppresses net mixing losses of biomass from the shoals. The close relationship between shoal and channel chlorophyll testifies to the thorough mixing between the two regions.

The relationship between the entrapment zone and shoal biomass (and, presumably, productivity) is not a simple one. Rather than determining a unique biomass, the location of the entrapment zone appears to set bounds on a range of possible biomass levels. River flow therefore controls the range of possible chlorophyll concentrations and this range is more restricted both at high flows and at low flows. The maximum chlorophyll concentration occurs at about 250 m<sup>3</sup> s<sup>-1</sup>, the approximate center of the flow range that positions the entrapment zone in Suisun Bay. But chlorophyll values are quite variable within the range and it is clear that positioning of the entrapment zone is not the whole story.

An additional source of interannual variability in biomass appears to be consumption by benthic herbivores. Nichols (1985) detailed how the Atlantic soft-shell clam *Mya arenaria* and other estuarine benthic invertebrates become established in Suisun Bay during drought periods such as 1976-1977. The larvae are carried upstream in the river-induced gravitational circulation and are able to colonize sites in Suisun Bay when salinity increases during dry years. In 1977, the estuarine species achieved densities sufficient to filter the entire water column approximately once per day. Similar appearances of *Mya* in 1962, 1981, and 1985 in Grizzly Bay suggest that about 16 months of consecutive low river inflow were necessary for successful colonization to take place (Nichols et al. 1990). The return of higher inflows eliminates estuarine species, resulting in decreased feeding pressure from the benthic invertebrate community.

This relationship between prolonged low river flow and temporary invasion by estuarine benthic invertebrates may have been upset in 1987 by the appearance of the Asian corbulid clam *Potamocorbula amurensis* (Carlton et al. 1990). The clam was probably introduced from the western Pacific by the release of seawater ballast into San Francisco Bay in the mid-1980s. By 1987, *Potamocorbula* had become numerically dominant at shoal and channel sites in both Suisun and San Pablo bays, and was also present at some South Bay sites. The rapid spread has been attributed to a depauperate benthic community following the flood in early 1986, which resulted in a lack of competition from pre-existing species (Nichols et al. 1990). Low river inflow had again become prolonged for a period of 16 months by 1988, but *Mya arenaria* did not appear in its usual numbers, apparently excluded by the new arrival.

Low phytoplankton productivity may persist as long as conditions -- namely low freshwater flows -- favor estuarine benthic macroinvertebrates. Although riverine loading probably will increase once flows are restored, the same cannot be said of phytoplankton productivity. *Potamocorbula amurensis* is able to tolerate an extremely wide range of salinity (at least 1-30 %), suggesting that it will not be dislodged by the return of higher river inflows (Nichols et al. 1990). If so, enhanced grazing pressure from benthic invertebrates will continue, depressing local populations of phytoplankton and perhaps benthic microalgae. Lower microalgal productivity could therefore persist for some time.

As long as Delta discharge is low, organic carbon contributions from riverine sources should remain at depressed levels as well. As a result, the relative importance of organic carbon from riverine loading can only increase. Given the apparent dependence of chlorophyll on annual Delta discharge, the relation between organic carbon sources for the food web and the magnitude of Delta discharge may thus become even more clear with the presence of *Potamocorbula*.

The response of marsh export to river discharge is of interest. The magnitude of Delta outflow undoubtedly has some moderating effect on exchange between tidal marsh and open water. The smaller freshwater supply during drought conditions also should favor the spread of

estuarine macrophytes in their competition with freshwater macrophytes, changing the habitat areas available for higher organisms. But if the net effects on marsh export are damped compared to the response of organic matter loading and phytoplankton productivity, then marsh export may increase in importance during drought periods.

#### 6.5.1 **Delta**

Phytoplankton is the dominant source of primary productivity in the Delta. The steep-sided banks of the dredged sloughs and channels have greatly reduced the former contributions of emergent vegetation and their attached assemblages of algae and their consumers. Benthic algae are very limited in the Delta because of the combination of turbid water and depths that usually keep the euphotic zone well above the bottom. Dikes and dredges have removed most of the shallow habitat necessary for benthic algae or emergent vegetation from most of the Delta.

Substantial *in situ* production of phytoplankton occurs in the Delta. As it enters the Delta, water from the Sacramento River seldom contains phytoplankton concentrations greater than  $6 \mu g/L$ , halfway through the Delta chlorophyll·a concentrations average 10-12  $\mu g/L$ , and as it enters Suisun Bay it may carry from 10 to  $60 \mu g/L$  (Ball 1975; Chadwick 1972). This pattern of increasing phytoplankton abundance at greater distance downstream occurs throughout the length of the Sacramento River (Greenberg 1964).

Conversely, at times when San Joaquin River water carries phytoplankton concentrations of 240  $\mu$ g/L into the Delta at Vernalis, phytoplankton populations in more downstream sites are only 40 to 60  $\mu$ g/L. These results are primarily a result of the CVP and SWP pumping stations that withdraw almost all the plankton-rich waters of the San Joaquin (Ball 1975), thereby causing the less fertile waters of the Sacramento to flow up the lower channels of the San Joaquin.

As with Suisun Bay it is possible to document the decline in contribution of organic materials from improved sewage water treatment but there are insufficient data to allow estimation of the importance of such inputs to the food web of the Delta.

#### 6.6 Trends in zooplankton

Zooplankton populations are only sampled regularly in Suisun Bay and the Delta. The only data describing zooplankton populations in the rest of the Bay complex are for only one year each in South, Central, and San Pablo Bays, so no statements of trends are possible. Trends in data on zooplankton in the upper estuary have been analyzed as part of testimony for the State Water Resources Control Board (CDF&G 1987b) for the period from 1972 to 1985. A more recent analysis of data up to the introduction of the clam *Potamocorbula* is being developed and generally agrees with the trends reported in 1987 (Orsi et al 1991). The following discussion draws on both reports and on our own graphing of the data.

#### 6.6.1 Rotifera

Rotifer populations have sharply declined throughout the Delta, particularly in the San Joaquin River where they were formerly most abundant (CDF&G 1987). From 1972 to 1979 the population in the Delta declined to less than a tenth of their initial densities (Figure 18). In

Suisun Bay, where they were never very abundant, the decline was less severe. Since 1979 there has been no consistent difference in abundance of rotifers in the two areas. This decline has been less in the more marine species Synchaeta bicornis, than in the more freshwater genera Keratella, Asplancha, and Polyartha (Orsi et al. 1991). The decline in the Delta appears to be strongly associated with declining concentrations of chlorophyll a which formerly characterized the

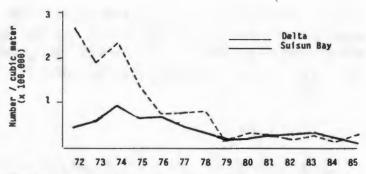


Figure 18 Mean densities of rotifers in 100,000 / m³, all species combined, from March to November in Suisun Bay (solid line) and the Delta (dashed Line). Modified from CDF&G 1987b.

areas of greatest rotifer abundance (CDF&G 1987b).

The most abundant rotifer in both the Sacramento and San Joaquin Rivers was Keratella in the early years of the study, it, along with the less abundant genera Polyartha and Trichocerca, underwent massive declines in abundance through the 1970s (Figures 19, 20). Synchaeta, the rotifer most abundant in Suisun Bay and least abundant in the Delta, did not decline as precipitously. In Suisun Bay, densities of all of the more abundant types were present at much lower densities through the 1980s than in the 1970s (Figure 21). The less common species of the genus Synchaeta are the only group to show no trend through time, although they also fall to record low densities in 1988, coinciding with the establishment of Potamocorbula amurensis in high densities.

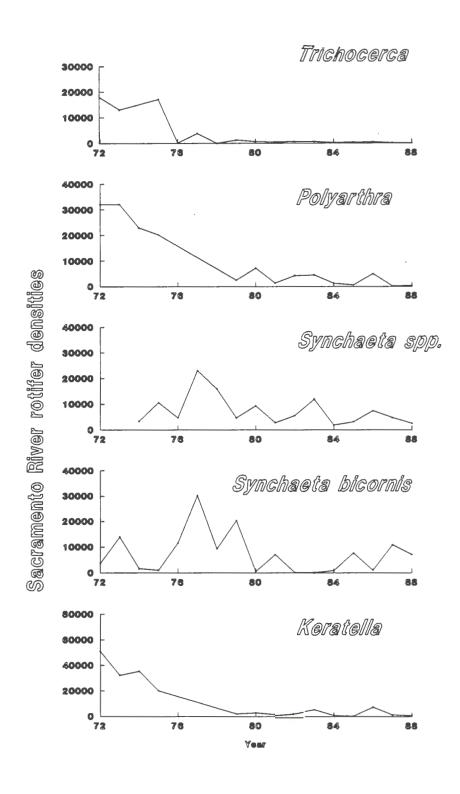


Figure 19 Mean densities per m³ of the abundant species of rotifers by year in the Sacramento River (data provided by CDF&G)

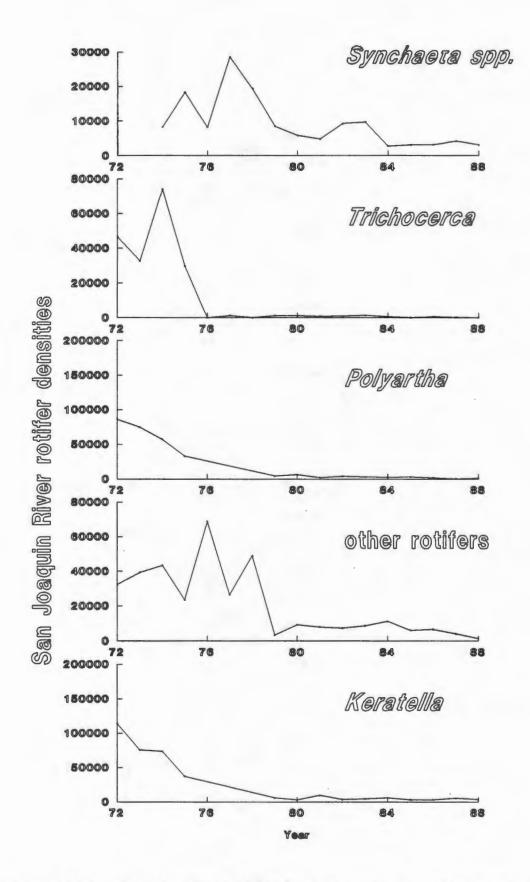


Figure 20 Mean densities per m³ of the abundant species of rotifers by year in the San Joaquin River (data provided by CDF&G)

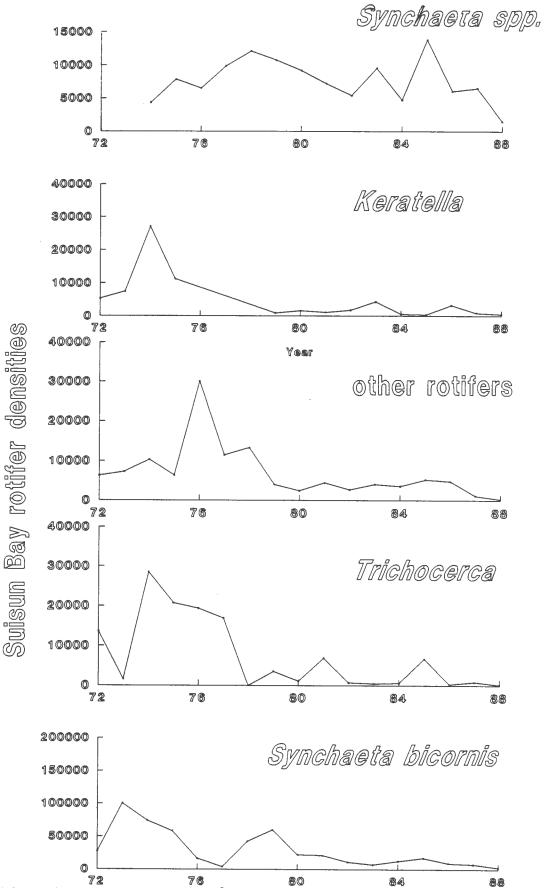


Figure 21 Mean densities per m³ of the abundant species of rotifers by year in Suisun Bay (data provided by CDF&G)

#### 6.6.2 Cladocera

Cladocerans have shown a longterm decline in abundance similar to that of the rotifers. However, the decline in Cladocera appears to have been more sudden, occurring in the late 1970's as the rotifers in the Delta reached the end of their period of decline. Population densities have remained at rather constant low levels but the lowest values for the three most abundant species all occurred in 1982-1983. A small recovery in abundance in all three taxa occurred through 1984-1986, but in recent years they have returned to extremely low levels.

Examination of the patterns of abundance of cladocerans through time for areas dominated by Sacramento River water, San Joaquin River water, and Suisun Bay shows the importance of outflow on cladoceran abundance and distribution. The sustained very high outflows of 1983 produced peak abundances of most cladoceran genera in Suisun Bay, although even these peaks are much smaller than the usual densities encountered upstream (Figures 22, 23, and 24). The moderately high outflows of 1986 produced peaks in abundance for all genera within the Delta but had little effect on Suisun Bay populations. Bosmina is the most common genus of cladoceran and shows the smallest proportional change in abundance through time; the less abundant Daphnia and Diaphanosoma show much greater declines in abundance following 1977.

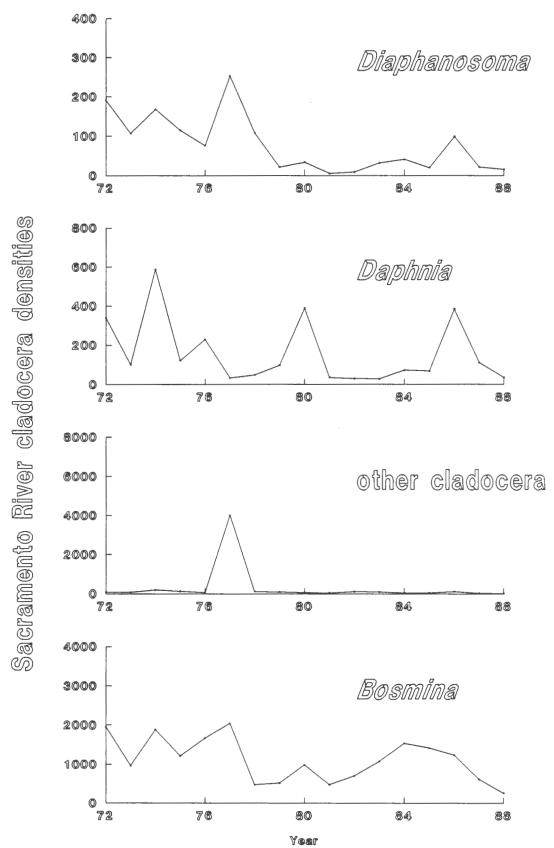


Figure 22 Mean densities of the three most abundant species of cladocerans in the Sacramento River (no./ per cubic meter). Data provided by CDF&G.

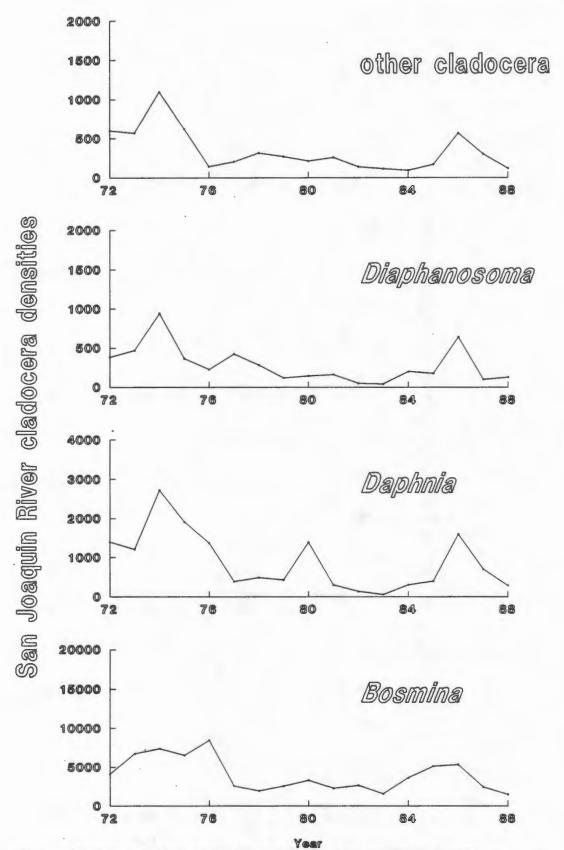


Figure 23 Mean densities of the three most abundant species of cladocerans in the San Joaquin River (no./ per cubic meter). Data provided by CDF&G.

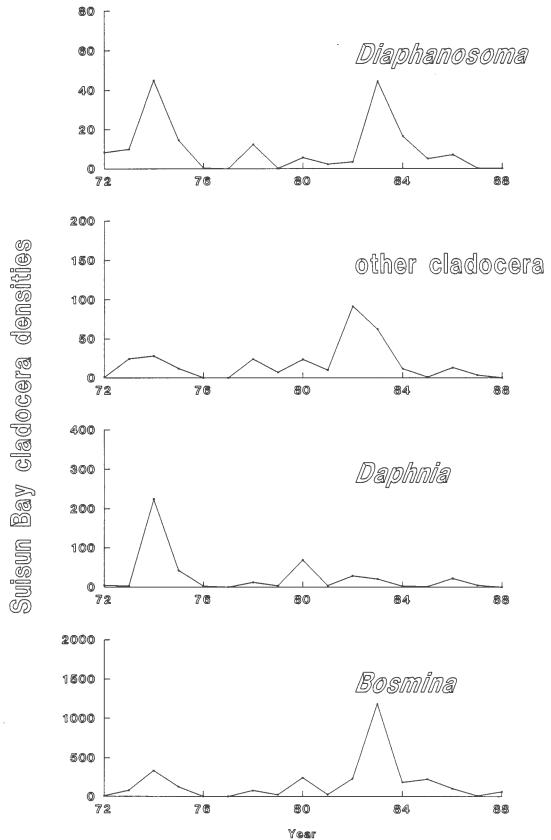


Figure 24 Mean densities of the three most abundant species of cladocerans in the Suisun Bay (no./ per cubic meter). Data provided by CDF&G.

### 6.6.3 Copepoda

Most species of copepods have undergone a severe, longterm declines in abundance (CDF&G 1987b). Only the marine species Acartia shows no evidence of a trend through time. This species is least abundant in the sampling area during years of high outflow and is usually most abundant when salinity in Suisun Bay is greatest (CDF&G 1987b). Invasion of the western Delta and Suisun Bay by Sinocalanus doerri in 1978 and by Pseudodiaptomus forbesi in 1987 was followed by declines in the abundance of Eurytemora affinis and the almost complete elimination of Diaptomus spp. (CDF&G 1987b; Meng and Orsi 1991). Most copepods, including Acartia, have been at record low abundances in Suisun Bay since the arrival and explosive spread of Potamocorbula amurensis.

Analysis of the dominant native copepod species in waters of the Sacramento River, the San Joaquin River, and Suisun Bay shows that the decline is sharpest in the rivers (Figures 25, 26, and 27). Eurytemora, overall the most abundant copepod in both rivers, declined in abundance in 1978 and has remained generally below average densities of 500/1 whereas in 4 of the 6 earlier years its average density exceeded 1000/1. Cyclops vernalis and Diaptomus spp. show sharp declines through the 70s in both rivers, although the Diaptomus decline stretches out to 1981 while C. vernalis was extremely rare by 1977. Both species showed a short-lived return to high density following the high outflows of February 1986. These mean densities are not adjusted for salinities and simple changes in water quality due to low inflows may be adequate explanation for the declines.

The introduced copepods, Limnoithona sinensis and Sinocalanus doerri, are predominantly found in freshwater. Due to increases in the abundances of these species the average densities of copepods in each river are still high in most years (Figure 28). The simple replacement of native species by exotics is not a complete picture because Sinocalanus doerri inhabits stations further upstream than those occupied by the formerly abundant Eurytemora affinis (Orsi et al. 1983), so measures of average abundance are inflated by the greater range of the introduced species. Nonetheless, densities of native copepods in areas where introduced copepods are now abundant are markedly lower. A mechanism for replacement may be selective predation due to the greater ease with which larval fish can feed on native copepods than on introduced species, at least some of which have more effective escape responses (Meng and Orsi 1991).

Within Suisun Bay only Eurytemora shows a consistent pattern of decline through time, and the decline is not as severe as at upstream sites. The most abundant copepod in Suisun Bay, Acartia, showed increased abundance in dry years until recently. As in the rivers, C. vernalis fell to very low numbers in 1977 but was increasing to its former levels until 1987. All species in Suisun Bay were at extremely low abundances in 1988, when the introduced clam Potamocorbula amurensis was at high densities and chlorophyll a concentrations failed to attain their usual seasonal peaks. Introduced species of copepods are generally not a large part of the populations in Suisun Bay, generally increasing in abundance there in response to periods of high outflow (Orsi et al. 1983).

Suisun Bay usually supports copepod densities about twice that found in the Delta (Figure 27), fluctuating between average densities of 2000-10,000/l while the average densities at river sites are usually between 1,000 and 4,000/l. Although downstream transport of copepods is thought to be important in controlling the abundances of freshwater forms in downstream areas (Orsi et al. 1983; CDF&G 1987) there is not an inverse relationship of copepod abundance in

the different regions in wet years. The high flows of 1983 led to low abundances in all regions whereas the high flows of spring 1986 did not lead to any apparent shift of the populations downstream.

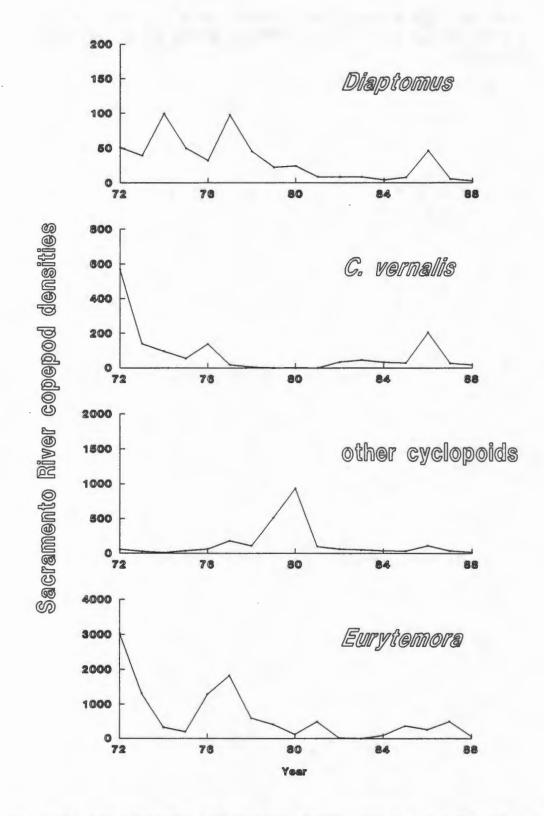


Figure 25 Mean densities of the four most abundant species of cladocerans in the Sacramento River Bay (no./ per cubic meter). Data provided by CDF&G.

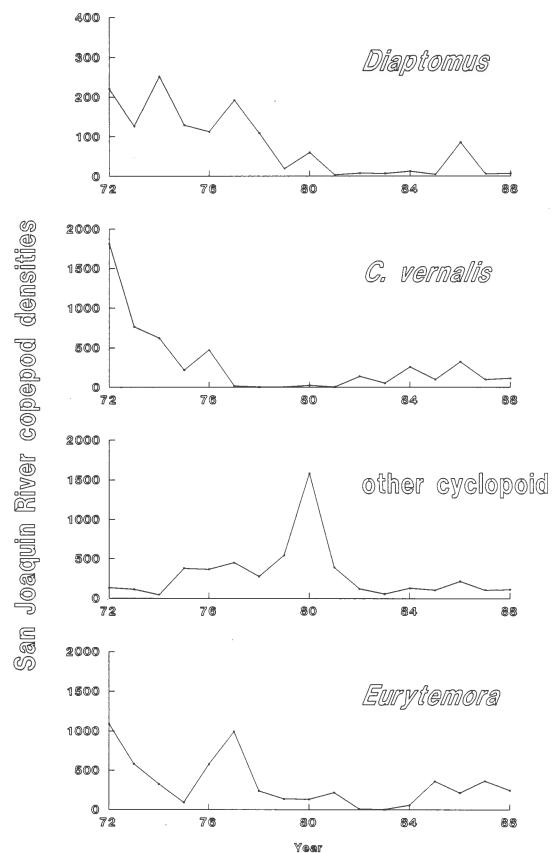


Figure 26 Mean densities of the four most abundant species of copepods in the San Joaquin River (no./ per cubic meter). Data provided by CDF&G.

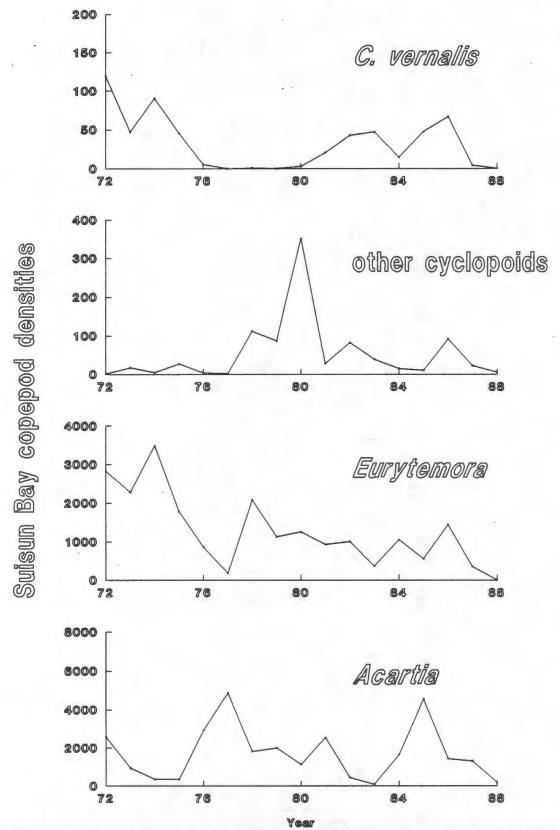


Figure 27 Mean densities of the four most abundant species of copepods in the Suisun Bay (no./ per cubic meter). Data provided by CDF&G.

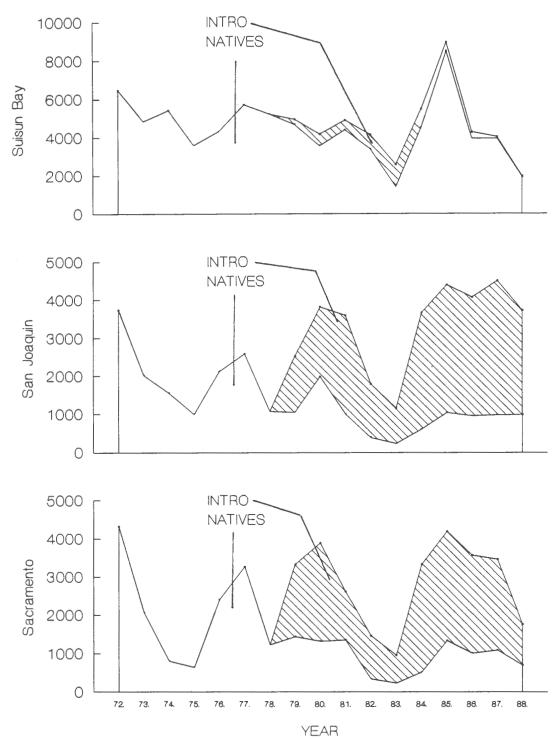


Figure 28 Comparison of densities of native and introduced copepods in three areas: Sacramento River, San Joaquin River and Suisun Bay (data provided by CDF&G)

### 6.6.4 Neomysis mercedis

Annual variability in abundance of *N. mercedis* can be accurately predicted from knowledge of chlorophyll a concentrations and either of the interconnected variables of salinity at Chipp's Island or delta outflows (Orsi and Knutson 1979). Studies during the drought of 1976-77 (Siegfried et al. 1979) suggested that the location of the null zone determines the annual fluctuations in *N. mercedis* abundance. If the null zone is in the deep channels of the main rivers, as happens when delta outflows are low, then chlorophyll a concentrations remain low. When outflows are higher, salinity at Chipp's Island is lower, and algal populations accumulate in the broad shallows of Suisun Bay. Presumably, this relationship between the location of the null zone and *N. mercedis* abundance is increased food supplies (mainly copepods which feed on the algae) for the shrimp when the zone is located in Suisun Bay. *N. mercedis*, because of its short life cycle, can respond rapidly to increases in prey abundance by increasing its production of young.

Regression analysis of the abundance of N. mercedis from 1968 to 1981 indicate that, in addition to outflow, the abundance of the copepod Eurytemora affinis has is significantly linked to the density of adult Neomysis (Knutson and Orsi 1983). Since Eurytemora affinis is the primary prey item of larger Neomysis that suggests to indicate that the Neomysis population is,

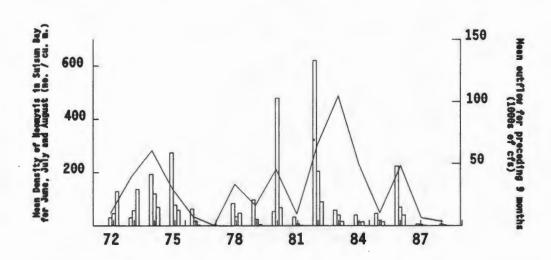


Figure 29 Abundance of *Neomysis mercedis* in July, August and September (bars) in comparison to previous mean outflow rates (line). Data from CDF&G and DAYFLOW.

at times, food limited.

All of the factors associated with low abundance of *N. mercedis* have been unfavorable in recent years: low outflow, high salinity at Chipp's Island, low chlorophyll a concentrations in Suisun Bay, greater water clarity, and low densities of *E. affinis*. Under the conditions in Suisun Bay, it is not surprising that populations of *N. mercedis* have been lower for almost all years of the 1980s than in earlier years. The hypothesis that the population was limited by preclation appears unlikely because most fish species which feed on *N. mercedis* have simultaneously declined in abundance. However, the current practice of introducing large

numbers of hatchery-reared juvenile striped bass into the Delta may provide a test, albeit unintentional, of this hypothesis.

Outflow, as one of this linked set of variables, is a partial predictor of N. mercedis abundance (CDF&G 1987b) and periods of drought in the late 1970s and 1980s coincide with the lowest recorded densities of the shrimp but the relationship is not simple (Siegfried et al. 1979; CDF&G 1987; Figure 29). Exceptionally high outflows appear to have carried N. mercedis out of their normal habitat, likewise drought periods coincide with very low N. mercedis densities. In intermediate years, higher outflows that are to be associated with lower salinities in Suisun Bay and the western Delta and with higher concentrations of chlorophyll a seem to support larger populations of the opossum shrimp. However, other factors seem to have controlled abundance of Neomysis in recent years of moderately high outflow, because occasional peaks in abundance occur during a period of general decline. It is worth noting that in the first years of the study abundance increased through the summer months, which was also the pattern in 1963 (Turner and Kelley 1966). Since 1974, the peak abundance of Neomysis has occurred earlier and rapidly declined through the summer.

The recent effects of drought on *Neomysis* have been exacerbated by the extremely low levels of chlorophyll a in Suisun Bay since the establishment of *Potamocorbula amurensis*. The different mechanisms presumed to affect *Neomysis* abundance are probably all contributing to the low densities observed:

- 1. lower outflows restrict the entrapment zone to deeper, more upstream channels which are less likely to promote high densities of *Neomysis* (CDF&G 1987b).
- 2 lower outflows produce weaker landward currents along the bottom so that the ability of *Neomysis* transported downstream to return to the entrapment zone is reduced.
- 3. increased water clarity causes *Neomysis* to stay at lower depths to avoid light and predation, which may reduce the amount of time they can feed or during which they are being transported through the accumulated material in the mixing zone.
- 4. Eurytemora affinis food abundance has remained consistently low through recent years.
- 5. larger numbers of *N. mercedis* may be exported through the CVP and SWP pumps as a result of the increased proportion of inflow diverted during drought years. The location of the mixing zone within the lower river channels during dry years (Siegfried et al. 1979) increases the vulnerability of *N. mercedis* to such displacement.

Neomysis populations have not shown the sort of consistent declines shown by most other elements of the zooplankton. The trend through time is not significant because the population has occasionally rebounded to high densities (CDF&G 1987b; Orsi et al. 1991).

### 6.7 Trends in fish populations

Two species of fish of the Sacramento-San Joaquin Estuary have received the most attention from biologists: chinook salmon (*Oncorhynchus tshawytscha*) and striped bass (*Morone saxatilis*). Both species are anadromous and are of great economic importance but differ from each other in almost every other way. We review recent descriptions of the biology, status and trends for these two species and then examine the data and studies for several other species of the estuary.

### 6.7.1 Chinook salmon

Chinook salmon grow to almost 1.5 m, larger than any other species of salmon. They make up the largest commercial finfish fishery near San Francisco and also support a very large sport fishery in the ocean. In the Bay, which is open only to sport fishing, the fishery is much smaller. Marked fingerlings from

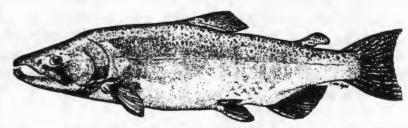


Figure 30 Chinook salmon. (Slightly modified from Moyle 1976)

the Sacramento-San Joaquin estuary have been caught in abundance as adults all the way up the west coast to Vancouver Island. The Central Valley supports the largest population of chinook salmon but the population has suffered very large declines of the wild stocks. It is now maintained to a large extent by hatchery operations.

Salmon abundance in the Sacramento-San Joaquin estuary prompted massive fishing efforts and the opening of the first salmon cannery in 1864 (Skinner 1962). The only quantitative statement on the early abundance of chinook salmon are the records of this company, which show export of 48 tons in the first two years of operation. More canneries opened and more commercial fishing led to a mean annual catch of more than 3,000 tons until commercial salmon canning was banned in the Bay in 1919 (Skinner 1962). Except for a brief resurgence in the 1940s the commercial catch in the Estuary remained at low levels from 1920 to its end in 1957 (Skinner 1962).

Chinook salmon spawn and die in the tributaries or upper reaches of the Sacramento River and, to a lesser extent, in the San Joaquin River. Approximately half of the potential spawning sites were blocked by construction of Shasta Dam. Reproduction in the San Joaquin drainage was greatly reduced by construction of Friant Dam. As mitigation for the destruction of these fisheries, hatcheries were constructed and much of the population now consists of fishes raised to the fingerling stage in hatcheries.

Individual adult chinook salmon spend very brief periods in the Sacramento-San Joaquin Estuary during their upmigrations. Outmigrations of smolts are spread out over a longer period because they spend daylight hours along the edges of streams and usually slowly migrate downstream at night when outflow is low and the water is clear. Under higher flows and turbidities, daytime migrations may take place as well. However, the species is divided into four genetically distinct runs which travel through the estuary at different times so that it is possible to find adults and juveniles passing through the estuary in any month of the year when

temperatures permit (Figure 31). Adult salmon migrate through the estuary very rapidly, usually in a few days, with individuals of the endangered winter run passing through most quickly (Hallock and Fisher 1985). The only study of adult migration through the estuary to tag individual fish was conducted 25 years ago (Hallock 1970). Opening of the cross-Delta channel brings Sacramento River water into the central Delta and causes delays of adult salmon migration (Hallock 1970). Such delays can lead to failure of female fish to find appropriate spawning sites before having to release their eggs. High temperatures, low oxygen concentrations and high biological oxygen demand are interrelated variables which have been shown to block migration of adult salmon of the San Joaquin Basin. Increased sewage treatment (particularly in Stockton), operation of New Melones Dam to provide greater flows, improved water quality and a temporary barrier at the head of Old River have improved spawning success of Stanislaus, Merced and Tuolumne River populations (USFWS 1987). The shortage of water in all three drainages during the 1985-1991 drought resulted in the lowest returns on record to the San Joaquin drainage (CDF&G unpublished data). High diversion rates relative to flow lead to decreased ability of the runs to find their natal streams (USFWS 1987).

Passage through the Delta is a critical step in chinook salmon smolt survival (USFWS 1987; Herrgesell 1990). Tagged smolt releases further downstream in San Francisco Bay show greater

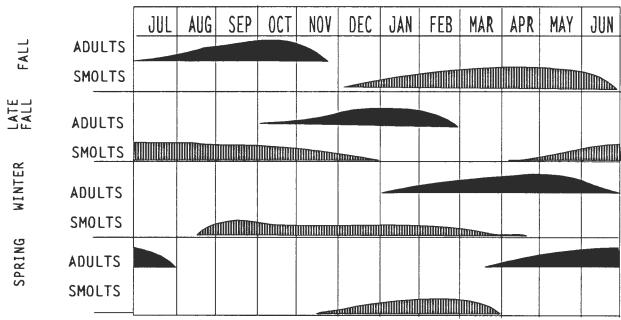


Figure 13 Periods of migration for the four runs of chinook salmon through the Sacramento-San Joaquin River system. (modified from USFWS 1987)

survival and rates of return than releases in the Delta or upstream areas (USFWS 1987). The large number of hatchery raised fish makes it difficult to discern the factors affecting the production by wild populations. After hatching, wild smolts spend extremely variable periods of time rearing in fresh water before beginning their downstream migration. Although the potential exists for smolts to migrate through the Delta in every month of the year, smolts are rarely observed from July through September due to high temperatures (USFWS 1987). Smolt migration through the Delta has been estimated at 9 to 11 miles per day (Herrgesell 1990) and at 3 to 20 miles per day (USFWS 1987). Migration rate through the Bay and Sacramento River side of the Delta is slower than in the upper reaches of the rivers and does not seem greatly

affected of flow rates as it is in more upstream reaches (USFWS 1987). Migration of smolts through the San Joaquin portion of the Delta, however, does seem to be related to flow. During their passage through the Delta, fall run smolts are particularly liable to be to suffer increased mortality if they enter the Central Delta (USFWS 1987). Passage through the Central Delta is detrimental to smolts because of warmer temperatures, increased predation rates, longer migration routes, areas of reverse flow in river channels, and entrainment by agricultural and export pumps (Herrgesell 1990).

A high correlation has been shown between outflow and most measures of smolt abundance and survival (Figure 32; USFWS 1987). The correlation appears related to the interrelationships between flow, water temperature, and the percent of flow diverted to the central Delta. Salmon smolt survival decreases as water temperature and percent of flow diverted into the central Delta increase.

To separate the effects of several factors affecting smolt survival on their passage through the Estuary, the Interagency Ecological Study Program performed an experimental series of releases of hatchery fish in 1989. Fish were released:

- 1. at various sites to examine the effects of different migration routes.
- 2. at the same sites in different months with the same outflow to investigate the effects of temperature.
- 3. above and below Walnut Grove when
- diversion gates of the Cross-Delta Channel were open and when they were closed in order to determine degree of impact of the cross channel operations on outmigration.

Results from these studies indicated that

- 1. shorter migration routes which avoid the Central Delta appear to be beneficial for smolt outmigration.
- 2. smolt survival increased at lower temperatures
- 3. survival of smolts released above the Delta Cross Channel was lower when the gates were open.

Within San Francisco Bay, a concern of how conditions may affect salmon numbers is through the dumping of dredge spoils at Alcatraz Island, which may reduce entry of adults into the estuary (Quinn 1990).

Because habitat loss has more greatly reduced the abundance of other runs, because operation of Shasta Dam favors spawning of fall run, and because hatchery production is mainly of fall run fish, the fall run now accounts for 90% or more of the 200,000 to 1,000,000 salmon of the ocean fishery (USFWS 1987). The amount of disruption of the fall run has also been less in the Sacramento River than in the San Joaquin River so that recently, the San Joaquin River accounts for 1 to 22 percent of the fall run spawners (Herrgesell 1990).

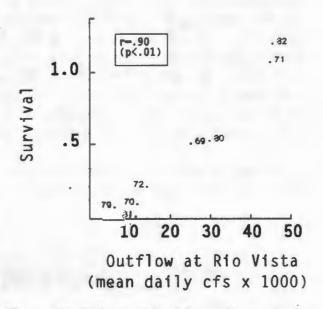


Figure 32 Relationship of smolt survival to mean daily outflow during outmigration. Label numbers indicate year of outmigration (modified from USF&WS 1987)

The most reduced run is the winter run which was listed as endangered by the state after its population was estimated to be less than 500 fish (Williams and Deacon 1990; Williams and Williams 1991). Listing as endangered had been proposed when the species had earlier declined from regular population sizes of 20,000 to 2,000 (Figure 33; National Marine Fisheries Service 1987; Williams and Williams 1991). Like the fall run, the winter run spawn primarily in the main stem of the Sacramento River. However, spawning and incubation occur from May through September and low flows during this period lead to lethally high water temperatures. Prior to construction of Shasta Dam the run had spawned in the cold, spring-fed waters of the McCloud River. Shasta blocked access to these spawning grounds but still provided a source of cold water for spawning; construction of Red Bluff Diversion Dam reduced access to the waters below Shasta Dam. The ability of the winter run to recover its former numbers is further reduced because adults return to spawn after only two or three years at sea; therefore adults are smaller than in other runs and have a proportionately lower fecundity (Hallock and Fisher 1985).

Spring run adults enter tributary streams and hold in them through the summer months while their gonads mature (Marcotte 1984). This life history pattern has made them very sensitive to dams that block their access to holding pools and spawning sites or which reduce summer flows through their holding pools or spawning sites so that temperatures rise to stressful or lethal levels (Moyle et al. 1989). Because of widespread damming of streams and the sensitivity of the spring run to damming, they have declined from being the most abundant run in the Sacramento Valley to populations of only 3600 to 17,000 in the years between 1969 and 1980 (Marcotte 1984). However, the spring run which

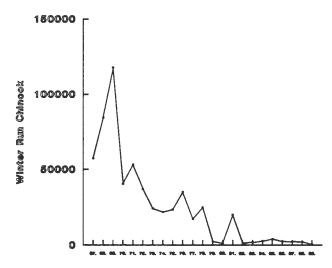
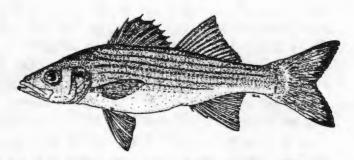


Figure 33 Estimated population of returning winter run chinook salmon in the Sacramento River. Data from Moyle et al. 1989.

spawns in the upper Sacramento River has been relatively stable at around 15,000 fish, although its genetic integrity is doubtful. Likewise the run on the Feather River is stable at around 2,000 fish, although it is largely supported by hatchery production. Runs of wild fish in Butte, Big Chico, Mill, and Deer Creeks have all declined to less than 1,000 fish total, and are continuing to decline (Campbell and Moyle 1991). Earlier construction of LaGrange Dam on the Tuolomne River doubtless destroyed a salmon population in that stream but data prior to construction are scant. Construction of Friant Dam provided a well-documented extermination of the spring run in the San Joaquin River (Warner 1991).

### 6.7.2 Striped bass

The introduction of striped bass (Morone [previously Roccus] saxatilis) in 1879 led to a commercial fishery in the estuary within 10 years (Craig 1928). The spectacular success of this fish is very similar to that of American shad which were introduced in 1871 and Figure 34 Striped bass. (from Moyle 1976) supported a commercial fishery 8 years



later (Skinner 1962). Both successes can probably be attributed, in large measure, to the anadromous nature and semi-buoyant, non-adhesive eggs of both species. Being anadromous brought the initially few adults together in a limited area so that the broadcast eggs and sperm would be likely to find each other, while the young were carried downstream and did not have to deal with a river that was naturally very variable in flows and temperatures and which was being massively affected by human actions. The semi-buoyant eggs were not susceptible to suffocation by the tremendous quantities of silt released into the streams by hydraulic mining.

However, the striped bass introduction differs in one major respect from that of American shad. American shad travel widely in oceans and, after their planting in California, they were found to naturally invade many other rivers on the Pacific Coast (Moyle 1976). Striped bass have been captured from central Oregon to southern California but most of the population of the Sacramento-San Joaquin system does not travel more than 40 km from the Golden Gate during their time in the ocean (Chadwick et al. 1977; Stevens et al. 1985).

Striped bass is the principal sport fish caught in San Francisco Bay. In the Delta more angler hours may be spent in pursuit of catfish and crappie, but the large industry supporting the needs of striped bass enthusiasts make the striped bass more important economically. The subsidiary industries surrounding striped bass fishing (boats, marinas, and paraphernalia) are estimated to bring \$45 million into the local economies (Meyer Resources Inc. 1985). Declines in the fishery since 1970 are estimated to have cost the state more than \$28 million per year (Meyer Resources Inc. 1985).

The tremendous growth of the striped bass population, from two initial plantings of 132 fish in 1879 and 300 fish in 1882, reflects the enormous fecundity of this species (Skinner 1972). Females commonly broadcast from 500,000 to 4.5 million eggs (Hassler 1988) although estimates range from 11,000 (Moyle 1976) to a high of 5.3 million (Hollis 1967; Hardy 1978; Wang 1986). San Francisco Bay in the 1880s allowed many eggs to grow to adulthood. By 1889, the striped bass fishery was landing more than 454 tons each year until 1915 (Smith and Kato 1979). Either through overfishing, habitat degradation or the usual decline in abundance following the successful introduction of a species, the population of appears to have begun declining in the early years of the 20th century. Finally, in 1935, commercial fishing for striped bass was banned. Despite the removal of commercial fishing the striped bass population seems to have continued its decline. Catch per angler per year steadily dropped from more than 20 fish in the 30s, to more than 10 in the 40s and finally less than 10 through the 50s (Skinner 1962). To some extent the decline was attributed to degradation of the Bay as fish habitat. Former popular fishing grounds in South Bay and in the Napa River were abandoned both by striped bass and anglers due to pollution and habitat loss (Skinner 1962). Identification of the declining trend in catch per angler (Skinner 1955, cited in Skinner 1962) led to tighter restrictions and catch limits so that later catch per angler figures are not comparable. However, the fishery continued to attract and satisfy a large number of Bay area anglers until the late 1970s (Meyer Resources Inc. 1985). Given that the population of anglers was probably increasing in proportion to the growth of the human population overall, it is impossible to know if catch per angler reflects the size of the striped bass population.

Scientific monitoring of the striped bass population began in 1959 and in the early years of study the population showed greater production of young in most years than it has shown most recent years. Examination of the first 15 years of the study showed a high correlation of 38 mm bass abundance with Delta outflow (Turner and Chadwick 1972). A regression equation, based on Delta outflow, very effectively modeled striped bass abundance.

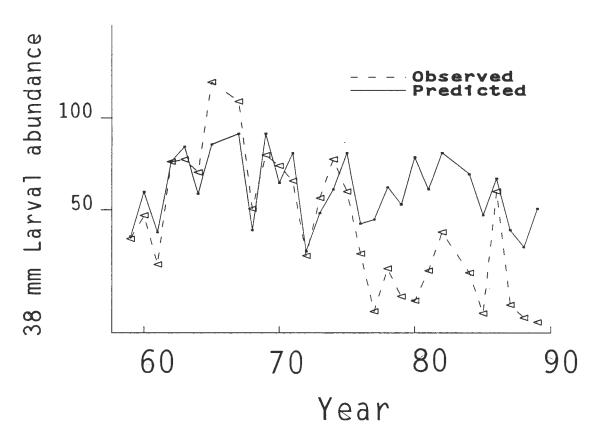


Figure 35. Comparison of actual striped bass index values with those predicted from a regression equation based on outflow.

The mechanism by which outflow controlled larval recruitment was unclear. High outflows were thought to provide (Turner and Chadwick 1972; Stevens 1977):

- 1. larger nursery areas so that intraspecific competition would be minimized; 2. more shallow habitats producing more primary productivity leading to greater food abundance for larval bass;
- 3. more water to dilute pollutants;
- 4. greater turbidity and less dense concentrations of young to reduce predation;
- 5. smaller danger of entrainment into diversions from the Delta.

Unfortunately, for most of the following years, the model seriously overestimated the abundance of young bass (Figure 35). The failure of the model to accurately predict striped bass production coincides with a severe decline in striped bass abundance. Population estimates for the total population of three year old fish in the estuary were between 860,000 to 1,210,000 for the years prior to 1976; from 1977 onward the population ranged from 380,000 to 650,000 (Herrgesell 1990).

A variety of causes for the decline have been put forward with varying degrees of supporting evidence. Among those who fish for striped bass a popular explanation was based on the presence of ulcers on the left side of many adult striped bass. The possibility that a new disease was decimating the population was discussed in the popular press. However, the tapeworm (Lacistorhynchus tenuis) responsible for the ulcers appears to be neither virulent nor abundant enough to produce such a massive change in the population. The following summary of factors sufficiently widespread to be responsible is based largely on the discussion in Herrgesell (1990).

#### 6.7.2.1 Possible mechanisms for the decline

Toxics. Toxic contamination of the estuary increased several-fold during the mid 1970s as rice farmers switched to growing short stem rice which entailed higher applications of pesticides (Foe 1989). Concentrations high enough to kill fish were found during monitoring surveys in several sloughs near rice fields in the Sacramento Valley. Concentrations calculated to have occurred in the mainstem of the Sacramento River during the 1977 drought may have posed a serious threat to striped bass larvae (Foe pers. comm.). Studies of the toxicity to striped bass larvae and to N. mercedis of drain water entering the Sacramento River have been undertaken by the California Regional Water Quality Control Board - Central Valley Region (Foe 1989) and the Department of Fish and Game (Finlayson et al. 1991). Both studies demonstrated acute toxicity of the water to N. mercedis. Bioassays using striped bass larvae showed toxicity when conducted by the University of California, Davis for the Water Quality Control Board but tests by CDF&G did not. Differences in results may be due to different salinities at which the tests were run (Foe pers. comm.). Release of contaminated water from rice fields coincides closely both in time and space with the spawning of striped bass (Foe 1989). Calculations of the likely concentrations of toxics in the river in each year since 1977, when the rice growers began much greater use of toxics, accounts for 42% of the difference between expected and observed striped bass recruitment (Foe 1989).

Other evidence of the influence of toxic contamination has come from histological work performed by D. Hinton and W. Bennett of the University of California, Davis. Liver sections from larvae from the Sacramento River show much higher incidence of malformation than larvae from elsewhere. No quantitative estimates of mortality due to toxic compounds are available.

Larval starvation. The composition and abundance of food for larval bass has changed drastically since 1979. Introduced copepods, principally Sinocalanus doerri, have partially replaced the formerly abundant copepod Eurytemora affinis (CDF&G 1987b). In feeding experiments striped bass larvae, when they first start to feed are much more adept at capturing the native E. affinis and Cyclops spp. than they are at capturing the introduced S. doerri and slightly less adept at catching Pseudodiaptomus forbesi (Herrgesell 1990; Meng and Orsi 1991). The reason for the failure of larvae to feed effectively on the currently abundant Sinocalanus seems to be that the introduced species has more effective escape responses. However,

histological analysis of striped bass larvae collected from the wild have failed to show any signs of starvation (W. Bennett UCD, pers.comm).

Laboratory feeding experiments with striped bass have established a surprisingly tight relationship between food density and larval survival (Figure 36). Estimates of larval mortality rates and food abundance in the Sacramento-San Joaquin estuary were compared to those expected from these laboratory studies. Although food rates are lower than in most of the laboratory studies, mortality rates are substantially higher than expected (Figure 36). Thus, larval bass in the estuary are dying more rapidly than larval bass at similar food densities when held in the laboratory (Herrgesell 1990). The only factor expected to kill striped bass in laboratory feeding tests is starvation; if starvation

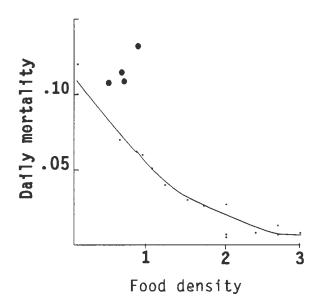


Figure 36 Relationship of food abundance and mortality in laboratory conditions (line and small dots) to conditions in Delta (large dots).

happens in the field, however, it is likely that slower growing or unhealthy fish would suffer increased mortality from other sources. Food densities are much lower than any feedings under laboratory conditions and growth rates are generally half of those observed under any laboratory food densities except complete starvation (Table 7). In short, starvation appears to be a reasonable expectation for young striped bass but they show no evidence of it either in their degree of stomach fullness or in histological comparisons with fish that are known to be starved. The decrease in food abundance and the abundance of less easily captured prey species, may have little to do with the striped bass decline but may make more difficult the recovery of the population.

Table 7. Growth rates of striped bass from various laboratory measurements compared to estimates from field measures in the Sacramento-San Joaquin Estuary. Measurements from Herrgesell 1990 are field estimates. (modified from Herrgesell 1990).

Source	Food density	Growth (mm/d)
FIELD	(log no./L)	(IIIII/U)
Herrgesell 1990	.6	.16
N	.7	.16
W	.77	.19
м	.83	.22
LABORATORY		
Daniel 1976	0.0	.036
Daniel 1976	30.0	.33
Chesney 1989	50.0	.30
н	100.0	.33
10	100.0	.36
Houde and Lubbers 1986	100.0	.22
Chesney 1989	250.0	.40
Houde and Lubbers 1986	500.0	.36

The most recently introduced clam, *Potamocorbula amurensis*, has developed large populations in Suisun Bay, which is the principal nursery area for larval striped bass. Filtration by this clam is presumed to be responsible for removal of phytoplankton and consequent failure of zooplankton populations to attain their normal densities. Because the clam was not present in the Bay until long after the population of striped bass had declined it is not possible for it to have been responsible for the decline. If it persists at its present high densities, however, it is possible that it will make restoration of the striped bass population much more difficult.

Hydrology. The decline in larval abundance, and the failure of the earlier regression model to accurately predict larval abundance, was most pronounced in the Delta (Chadwick et al. 1977). The only year since 1976 when predicted larval abundance based on outflow equalled actual larval abundance was in 1986 when flows through the Delta were augmented throughout the spring as a result of record rainfall in February. In Suisun Bay there was an abrupt decline in larval abundance during the 1976-77 drought. In the Delta the decline seems to have begun in 1971-1972 and to have been more gradual. In Suisun Bay, larval abundance has occasionally returned to former levels and both regions showed high abundances in 1986. However, since the start of a long drought in 1987, larval abundances have declined in both areas so that the 1990 overall index was the lowest ever recorded.

This pattern of more consistent decline in the Delta has focussed attention on mortality causes in the Delta. Movement of eggs and larvae into the Central Delta were they are subject greater mortality due to entrainment by various diversion is the most obvious control on larval mortality in the Delta. Additionally, 1977 was a year of much higher larval survival than expected for

the low level of outflow which is only easily explained by reference to the restricted amount of water diversions by SWP and CVP that year (Herrgesell 1990).

Testing of a regression model based on both outflow and diversion not only accounted for the anomalous survival of 1977, but provided much tighter correspondence between predicted and actual larval abundance for all years. Using these two variables and inserting a lag term of 5-8 years to allow the larvae to grow to maturity also accurately accounted for the observed drop in egg production in 1976-77 (Herrgesell 1990). Declining egg production may be a symptom rather than a cause of smaller population size (but see below).

The current year-round diversion of most San Joaquin River water toward the export pumps has greatly reduced recruitment from adults spawning in the upper San Joaquin. Unfortunately, there is no estimate of production from the San Joaquin River prior to the decline so it is impossible to determine how much production has been lost there. The commercial fishery in the 1800's was much more productive in the San Joaquin River (Skinner 1962). The banning of commercial fishing in 1935 also greatly reduced the availability of data on the distribution and abundance of this species. In 1986 the most intensive storm in California records produced an extremely large outflow volume and, for much of the spring, outflow greatly outweighed exports. This was the only year since 1977 when abundance of 38 mm larvae matched the prediction of the outflow-alone model. It has been argued (by J. Turner with challenges from D. Stevens) that this was largely due to successful reproduction in the San Joaquin River. However, the predicted strong year class of spawners resulting from the 1986 season failed to materialize.

Changes in egg production. A smaller adult population must produce fewer eggs and it has been argued that the decline in recruitment due to entrainment by water project operations may have produced a subsequent adult population size that does not produce enough eggs to maintain the population (Herrgesell 1990). Estimates of egg abundance are far below half of what they were prior to the decline (Figure 37). The lower egg production figures show a five to eight year lag with the estimated impacts of water diversions, due to the bulk of egg production coming from 5 to 8 year old fish. This explanation is supported most strongly by the apparent consistency between pre- and post decline measures of larval survival between each size class. Correlations between one larval size classes and the next are strong and suggest that the initial abundance of eggs should cascade through the larval stages and control recruitment. Decreased egg production may be simply a

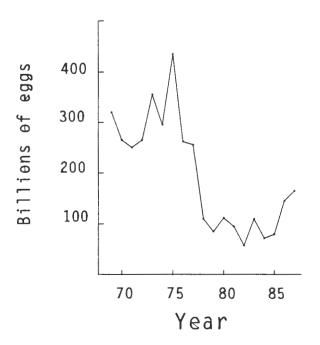


Figure 37. Estimated numbers of eggs produced by adult striped bass population in Delta. (from Herrgesell 1990).

necessary consequence of a smaller adult population size. It has been frequently pointed out that the initial planting of striped bass, which grew to immense numbers in only a few years, was

less than a thousandth of the estimated adult population today. This argument overlooks the complete restructuring of the Delta into a much less suitable habitat for striped bass than it was 120 years ago. The Delta today may allow a smaller proportion of eggs to hatch and so egg production now may be insufficient to maintain the population whereas a much smaller population of colonizers flourished in the 1800s.

# 6.7.2.2 Conclusions

Increased loss of eggs and larvae into the hazardous Central Delta is the only well-documented and sufficiently powerful mechanism to explain the continuing destruction of the striped bass fishery. Estimates of effective reduction from entrainment were 73 and 84% in the dry years of 1985 and 1988, respectively (Herrgesell 1990). These estimates contrast strongly with the estimated loss due to entrainment of only 31% in the wet year of 1986. The difference in losses between wet and dry years reinforces the density independent mechanism that is keeping populations low. Higher outflows move a higher percentage of eggs and larvae out of reach of entrainment and higher diversions lead to higher percentages of entrainment of eggs and embryos. The fact that the percentage taken is independent of the number present, coupled with ever smaller numbers of eggs produced, makes the interaction of diversion rate and outflow the only adequate explanation for the decline of the population and its inability to rebound.

The failure of the population to return to former abundance levels because of fewer eggs implies several corollary conclusions about the biology of striped bass in the estuary. For low egg abundance to be the mechanism that regulates adult population size requires that mortality of all stages is not density dependent. Biological populations usually show resilience to perturbation because lowered abundance permits greater access to limited amounts of food or habitat. Density dependent mortality at any stage in the life cycle of an animal will serve to return the population to previous levels. The striped bass population has shown very little evidence of resilience, or even a lessening of the rate of decline. Entrainment is the only likely density-independent source of mortality on striped bass that may be large enough to produce the decline and which covers the full period of their declining egg production.

The possible importance of toxics or food scarcity on striped bass recruitment has been downplayed because there has been no detectable change in age specific mortality between the pre- and post-decline periods. If larvae are succumbing to pesticides or starving to death one would expect age-specific survivorship to decline. With a declining population but no increase in mortality, it is argued that the principal cause of fewer larvae must be fewer eggs. Dumping of toxic waste water into the spawning grounds is also argued to be an adequate way to reduce effective egg production.

Although the data and biological reasoning support hydrologic changes in the Delta as the cause of the striped bass decline, it is premature to reject the importance of other factors. The failure to find a difference in mortality rates for different age classes provides only weak grounds for restricting attention to egg production and entrainment. Statistically, failure to reject the hypothesis of no difference is not the same as saying no difference exists (Steel and Torrie 1960). Failure to discern a significant difference may be attributed to the very small sample size of only five years, or to data which are inherently too variable to allow the identification of a small difference in means. Even small differences in mortality rates at early life history stages would be enough to account for a major reduction of the adult population. However, mortality rates from a variety of measures are in general agreement. The association

of increased diversions and decline in predicted striped bass production provides the most conservative explanation for the continued low production of striped bass abundance and their lowered egg production.

The case for larval starvation is based on lower growth rates and higher mortalities in the estuary than those recorded from laboratory studies. The replacement of native copepods by exotic species, particularly *S. doerri*, is considered to be a possible contributing factor. Although striped bass in the field consume *Sinocalanus*, laboratory studies show that they are much less successful at capturing them than they are with formerly abundant *Eurytemora*. Finally, the introduced clam has substantially reduced zooplankton densities in Suisun Bay, but they did not enter the estuary until ten years after the decline of striped bass. The clam may make recovery of striped bass populations difficult but it cannot have played any role before 1986. Countering this evidence is the observation that the histological changes accompanying starvation are absent from most larvae collected in the field. In addition there is a lack of persistently lower survival rates during the larval period or the period between 9 and 38 mm.

The evidence for the importance of toxics rests on the concurrent shift to heavy use of new pesticides at the time of the first drop of striped bass larval abundance from that predicted by outflow. Spawning grounds of striped bass in the Sacramento River are within the areas where rice fields discharge toxic wastewater into the river. There is no direct evidence that levels of pesticides in discharged waters from these rice fields have been high enough to kill sufficient larval bass in all years to account for the persistent decline.

However, several factors are likely to have contributed to the drop in abundance of the adult population and to the continued low production of larvae. Even if toxics or changes in food abundance and catchability is not the primary cause of the decline, they are likely to make recovery efforts more difficult.

# 6.7.3 Sturgeon

Like most of the other harvested fish of the estuary sturgeon are anadromous spawners. However, early fishing efforts greatly reduced the populations long before any biological research could be done.



Figure 38 White sturgeon (from Moyle 1976).

Research in recent years has attempted to determine the spawning areas, migration patterns and seasons but with limited success.

Two species of sturgeon inhabit the Sacramento-San Joaquin estuary; the green sturgeon Acipenser medirostris, and the white sturgeon Acipenser transmontanus. The green sturgeon is much less abundant, but is usually more abundant species in smaller Pacific Coast estuaries. The California Department of Fish and Game caught and tagged 2,746 sturgeon in 1967 and 1968, of which only 54 were green sturgeon (Miller 1972). The green sturgeon is disdained by fishermen (Jordan and Everman 1923). Green sturgeon appear to spend a large part of their life in salt water and to migrate into the lower reaches of rivers to spawn. The very small population size has hindered scientific study of the species but it is believed to be declining in abundance throughout its range (P. Foley, UC Davis).

White sturgeon appear to be more strictly estuarine in their distribution (Miller 1972a, 1972b) than green sturgeon. Early fishing for sturgeon collected many fish and many large individuals. The fishery seems to have depleted a population which was slow to replace itself (Skinner 1962). All fishing was halted in 1917 until a sports fishery was reopened in 1954 (Skinner 1962). Increased participation in the fishery followed increased use of shrimp as bait rather than simple snagging; shrimp used include *Crangon spp.*, *Palaemon macrodactylus*, *Callianassa*, and *Upogebia* (Kohlhorst et al. in press). Exploitation rates are inversely proportional to survivorship rates but exploitation rates are directly proportional to population estimates (Figure 39). Patterns of mortality and abundance suggest that population size is controlled primarily through recruitment (Kohlhorst et al. in press). Increased popularity of the fishery has had its greatest effect in reducing egg production by about a third of what it was under previous harvest rates.

Recruitment in white sturgeon appears to be greatest in years of very high outflow; mean daily outflows below 1000 m<sup>3</sup>s<sup>-1</sup> during the spawning season are associated with consistently low year class strength, but outflows over 1500 produce very strong year classes (Figure 40; from Kohlhorst et al. 1991). Data from other surveys covering a longer span of years show intermediate year class strengths in years of outflow averaging between 1000 and 1500 m<sup>3</sup>s<sup>-1</sup>.

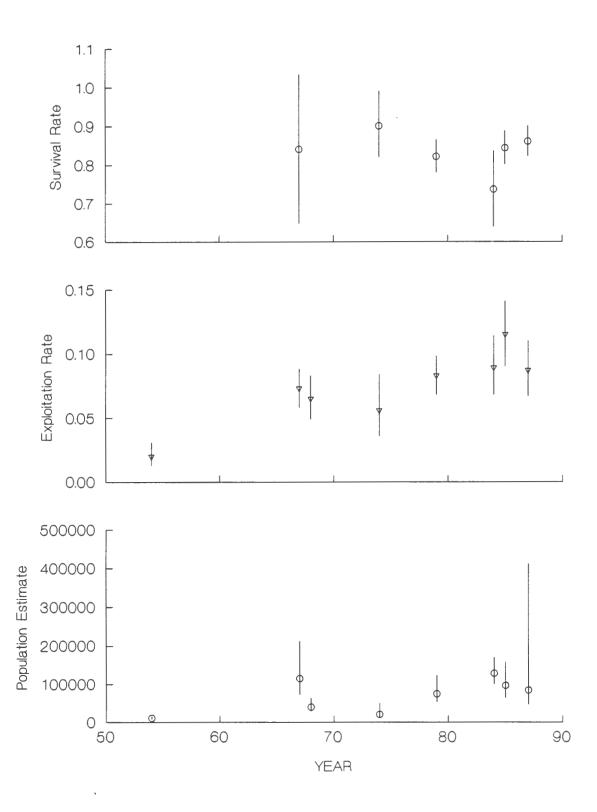


Figure 39 Means and confidence limits of survival, population size and exploitaton rates measured for white sturgeon population in the Estuary. (data from Kohlhorst et al. 1991)

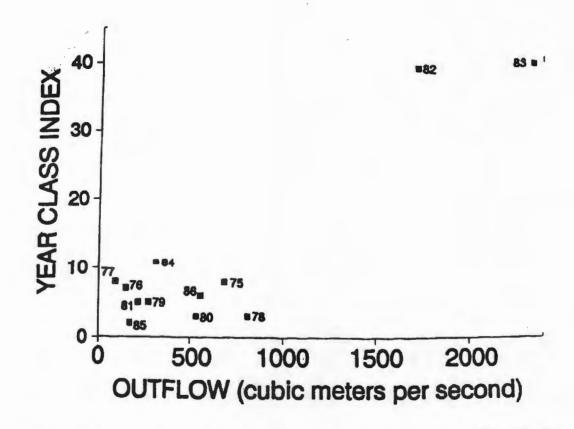


Figure 40 Relationship of white sturgeon production and outflow rates (from Kohlhorst et al. 1991)

### 6.7.4 Trends in the abundance of less studied species

# 6.7.4.1 Methods of comparison

Comparisons of changes in spatial distribution reveal other ways that species have responded to reduced flow regimes of the period from 1985-1988 in comparison to the variable flows from 1980-1984. Graphs of the abundance of each species of interest at each of the stations that were sampled in all years of the Bay Study are used to show these changes in distribution.

In examining the three main datasets for fishes of the Sacramento-San Joaquin estuary, we have attempted to compare fish which are similar in their habits but different in their distribution or patterns of occurrence in the estuary. For each kind we examine the distribution and trends, if any, for each species. Less abundant species exhibiting similar patterns are referred to where appropriate.

#### 6.7.4.2 Data sets used

Three data sets were used for most of these analyses: the CDF&G Midwater Trawl Survey, the CDF&G Bay Study, University of California and Department of Water Resources study of the fishes of Suisun Marsh.

Catches within the Fall Midwater trawl program are predominantly from September, October, November, and December for most of the years from 1967 to 1988. Description of the sampling regime is available in Stevens and Miller (1983). We primarily examined data from the month of September. The abundances from this month reflect the results of the preceding water year, data from other months showed effects of the onset of the next rainy season in the abundance and distribution of several species. In addition, the data from September gave a high number of stations that were sampled in each of 19 years. Other months were more haphazardly sampled, presumably because of foul weather and shorter days in the later months. Restricting the analysis to September also allows separation of the effects of one water year from the next; cursory examination of the data shows that years of high variability in outflow in October are years of large differences between the catches of September and those of October. Samples from stations from the upper reaches of the San Joaquin River were particularly irregular in later months. Unless stated otherwise, data presented here from the Fall Midwater Trawl (MWT) survey are for September for the stations:

MWT323 and 338 in upper San Pablo Bay,

MWT405, 412, 414, 416 and 418 in Suisun Bay,

MWT604 in Grizzly Bay,

MWT503, 507, and 515 in Honker Bay and upper Suisun Bays,

MWT606 and 608 in Montezuma Slough,

MWT710, 703, 705, 707, and 709 in the Sacramento River, and

MWT802, 804, 806, 810, 812, 814, 904, 906, 908, and 910 in the San Joaquin River. Each of these 28 stations was sampled in all years from 1967 to 1988 except 1974, 1976, and 1979. Data from other stations are used to compare with other data sets in less sampled areas. A single depth measurement (m) was used to characterize each study site for the length of the study, although factors such as tide and outflow resulted in depths at each site varying as much as one meter among sampling times. Salinity and temperature are generally available only for the surface water.

The CDF&G Bay Study uses both midwater and otter trawls and samples throughout the bay complex in all months of the year. A full description of the sampling regime is available in Armor and Herrgesell (1985). Stations were excluded that were not sampled in all years. Use of the same sampling sites in all years allows us to avoid constructing indices of abundance, instead relying on simple catch per unit effort. No sampling was performed in December of 1980 and in most of our analyses we have excluded data from all December collections in order eliminate differences in catch due to seasonality so that trends across years could be identified. The 35 stations used included:

Ten stations in South Bay
Six stations in Central Bay
Eight stations in San Pablo Bay
Eleven stations in or adjacent to Suisun Bay

Depth was measured at each sampling location on each date but we have used the average depth to characterize the site. Salinity and temperature data are available for surface and bottom waters. This dataset spans the 9 years from January 1980 to December 1988.

The UC Davis/DWR sampling is confined to Suisun Marsh, at the uppermost end of the bay complex. Sampling has been monthly from January of 1979 to May 1990 at 17 stations in the shallow sloughs of the marsh. A full description of the sampling regime is available in Herbold (1988) and Moyle et al. (1985). Salinity and temperature data were taken at each site; stations are mostly less than 2 m deep and no evidence of stratification has been found.

Historical data sets used for comparison were those of Pearson (1989) for fishes of the South Bay and Aplin (1967) for fishes of South and Central Bay. Sazaki (1975) was consulted for evidence of distribution of fishes in the Delta.

Abundance data for species of interest were summarized for each month at each station and embayment by (1) number of individuals per trawl, (2) presence or absence of the species of interest, (3) number of individuals caught per month, and (4) total catch of the species per year. For species in which different stages are ecologically distinct we have separated the analysis for young, juveniles, or adults as necessary. Data on lengths were only available for the Bay Study and the last three years of the Fall Midwater trawl survey.

Data on flows are derived form the DAYFLOW data set provided by the Department of Water Resources: annual and monthly averages were calculated from the daily flows.

## 6.7.4.3 Planktivores

The planktivores of the Sacramento-San Joaquin estuary cover a wide variety of species with varying distributions and uses of the estuary, principally northern anchovy, Pacific herring, American shad, longfin smelt, Delta smelt and threadfin shad. Eggs, larvae, juveniles and adults of northern anchovy occur principally in the lower part of the estuary with a peak in abundance during the summer. Pacific herring adults only enter the Bay to spawn and the larvae feed in the Bay. Similarly American shad adults migrate into the estuary to spawn but they move through the Bay and spawn, mostly, upstream of the Delta. Adult longfin smelt live throughout the Bay, are seldom found outside the Bay, and migrate into the Delta to spawn. Delta smelt adults are found usually in Suisun Bay and the Delta and migrate into the Delta to spawn. Threadfin shad live in the Delta and upstream areas and are generally only found in the Bay complex as a result of high outflows in the fall and winter.

Northern anchovy maintain the bulk of their population in the coastal waters of California and invade the Bay on a regular, seasonal basis. Anchovies do most of their spawning outside of the Bay, although eggs and larvae are also abundant in the Bay. Adults and juveniles enter the bay in the late spring for feeding and stay until autumn.

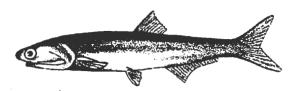


Figure 41 Northern anchovy. (modified from Eschmeyer 1983)

The northern anchovy population in San Francisco Bay has been described as a distinct subspecies (Hubbs 1925), but it seems likely that only three subpopulations are justified within the population of anchovies on the western coast of North America (Vrooman and Smith 1971). The San Francisco Bay anchovies are part of the Central subpopulation which spawns predominantly between mid-June and mid-August (Hunter and Macewicz 1980). Spawning takes place over a wide geographical range but most occurs near shore. Significant spawning within the Bay has been reported (Eldredge 1977; Wang 1986). Eggs are abundant within the Bay from May through September, however in coastal areas nearby spawning peaks from January to April (McGowan 1986). Thus, although the population is probably not a distinct subspecies, the fish spawning in the Bay are not under the same environmental controls on recruitment success as those spawning elsewhere.

Studies of the environmental requirements of northern anchovies have not led to any clear picture of how temperature, dissolved oxygen concentrations, or depth might control their distribution or abundance (Lasker and Smith 1977; Brewer and Smith 1982). In bays they are frequently found around sewage outfalls and die-offs due to low oxygen concentrations are common (Pacific Fishery Management Council 1983). Diet of northern anchovies is very diverse. Stomachs contained mostly crustaceans and other zooplankton but enough phytoplankton was found to suggest that it may be fed upon rather than incidentally consumed (Loukashkin 1970).

California northern anchovy populations bloomed after overfishing had removed most of the population of Pacific sardines (Baxter 1967). The fishery attempted to switch over to anchovies but after an initial heavy harvest the fish was found to be much less marketable and harvest rates declined (Skinner 1962). Extensive research was done on northern anchovy during the 1970's and early 1980's, partly in hopes of making them economically profitable without repeating the mistakes made with sardines (Brewer and Smith 1982; Chavez et al. 1977; Hanan 1981; Hunter 1977; Hunter and Coyne 1982; Hunter and Goldberg 1980; Hunter and Macewicz 1980; Hunter and Sanchez 1976; Lasker and Smith 1977; Mais 1981; O'Connell 1981; Richardson 1981; Scura and Jerde 1977; Spratt 1975; Stauffer and Charter 1982; Stauffer and Parker 1980). On the other hand, this species has been very little studied in the Bay, despite its overwhelming dominance by both number and weight (Armor and Herrgesell 1985; McGowan 1986).

Northern anchovy are the most abundant fish in San Francisco Bay. Aplin (1967) reported that northern anchovies made up 85% of the catch of 510,877 fish in Central and South Bay in 1963-1966. Some of the trawls made during Aplin's study contained catches of anchovies weighing "over 1000 pounds and could not be hauled aboard." Aplin (1967) also reports seeing feeding schools of northern anchovy in South Bay which "were estimated to contain several hundred tons of fish." The bait fishery on anchovies in the Bay took about 385 tons per year during the 1970s (Smith and Kato 1979). Estimates of adult biomass calculated from egg

densities suggest that in 1978-1979 peak biomass of northern anchovy was about 767 tons (McGowan 1986). Because of the large offshore population there is little concern over the impact of the Bay-based bait fishery on the total population, although little is known about the amount of fish collected in the ocean (Smith and Kato 1979).

Embryos and larvae of Northern anchovy use the Bay in distinctly different ways (McGowan 1986). McGowan's study includes only 12 contiguous months of sampling so that seasonality, per se, cannot be separated from non-seasonal changes in abundance. However, seasonality of the adult population is well documented and McGowan's conclusions generally agree with other short-term egg and larva sampling programs (Wang 1986). Eggs were found widely distributed within the Bay, while larvae showed lower densities in the stations most under the influence of oceanic water. Eggs were most abundant in areas of low zooplankton concentrations and clearer water. Stratification of the water column, and warmer surface water temperatures also characterized stations with high egg densities. Larvae were distributed within the Bay in a complementary pattern to eggs; larvae were found in areas of high zooplankton abundance and lower water clarity. Possibly eggs survive best in regions of low zooplankton populations due to lower predation rates while larvae require high concentrations of zooplankton for feeding success.

The large population of anchovies accounts for a large predation rate on zooplankton. Adult females consume 4.5% of their body weight in zooplankton each day and this predation may explain the lower densities of zooplankton in areas with high densities of anchovy eggs (McGowan 1986). Feeding by larvae and adults may play a role in making nitrogen available to phytoplankton; off southern California nitrogen concentrations are ten times greater in the wake of anchovy schools (McCarthy and Whitledge 1972). Consumption by adult and juvenile anchovy may account for 3,260 tons of copepods per year from the Bay. Migration to the ocean removes approximately 158 tons of new anchovy biomass from the Bay ecosystem (McGowan 1986).

Anchovies dominate the catch of both otter trawls and midwater trawls of the Bay Study. Fewer individuals are caught upstream of Carquinez Straits, but in the lower Bay northern anchovy comprise at least 70% of the number of fish caught each year. In Suisun Bay, during the first four years of the Bay study, longfin smelt outnumbered anchovies in three of the four years. Since 1984 anchovies have been the most numerous species in the midwater trawl in all embayments. In most years northern anchovy are most abundant in Central Bay, and generally more abundant in San Pablo Bay than in South Bay.

The Fall Midwater trawl survey, in the stations considered here, has only 2 of the 28 stations in the lower Bay where northern anchovies are abundant. However, the anchovy catch at those stations makes them one of the most abundantly captured fish overall.

Northern anchovy are thought to avoid surface waters during the day (Baxter 1967). However, 95% or more of the Bay Study catch of anchovies in each part of the Bay were taken in the midwater trawl. The proportion taken in the otter trawl is markedly lower for Suisun Bay.

Northern anchovy are seasonally present in San Francisco Bay. Overall they enter the Bay in April of most years and appear to outmigrate in the fall. The sharpness of their seasonality

differs in the different embayments. In Suisun Bay and San Pablo Bay they peak in abundance later and disappear more rapidly than in Central and South Bay (Figure 43).

Differences of opinion exist over the effects of differing outflow regimes on the abundance of northern anchovy in the Bay (Pearson 1989). Overall, anchovies have been described as a species giving mixed response to outflow variation (Armor and Herrgesell 1985; CDF&G 1987) but in South Bay they have shown a slightly negative association with outflow (Pearson 1989). Northern anchovy abundance is largely independent among the various embayments. Spearman rank correlations of abundance across years for San Francisco Bay are non-significant for all three areas, but highest for Central and South Bay (South Bay vs Central r=.65, p<.10; South Bay vs San Pablo Bay r=.22; Central vs San Pablo Bay r=-.18). Thus, pooling the data for all embayments may mask different use of each embayment by anchovy in different years. Responses to flow also differ across the three embayments; for both Central and South Bay there is a strong positive correlation with outflow (r=.83, p<.01 for South Bay; r=.88, p<<.01for Central Bay). However, there is no apparent response to outflow in San Pablo Bay (r=-These results strongly support the earlier report of a mixed response of anchovy abundance to outflow (Armor and Herrgesell 1985; CDF&G 1987a). The difference in result between the two data sets would seem to be most easily explained by the more restricted geographic scope of Pearson's study, as suggested by Pearson (1989).

Two mechanisms seem most likely for the increased abundance of anchovy in downstream sites during wetter years: physical displacement of this surface dwelling species by surface flows of freshwater or greater aggregation by the species during wet years in regions that are more saline. If simple transport by water currents was the motive force then high abundances downstream should be linked to lower abundance in San Pablo Bay. The absence of any effect of outflow in San Pablo Bay suggests that such displacement is not at work.

Northern anchovies have been observed spawning in the Bay (Wang 1986), but most of the population spawns in the ocean and any contribution to recruitment by Bay fishes is probably small (Stauffer and Parker 1980). Young anchovies are first caught each year in the Bay prior to or simultaneous with the catch of older fish. Thus, many of the young caught in the Bay probably are transported in from the ocean by bottom currents. Anchovies are known to spawn repeatedly (Hunter and Macewicz 1980) but the smallest size classes of anchovies in the Bay appear only at the start of the season. The size distribution of northern anchovies in the Bay shifted to larger fish following *El Niño* in 1983 (Figure 42)

The spatial distribution of northern anchovy in the Bay between the early and late 1980s shows no general shift (Figure 44).

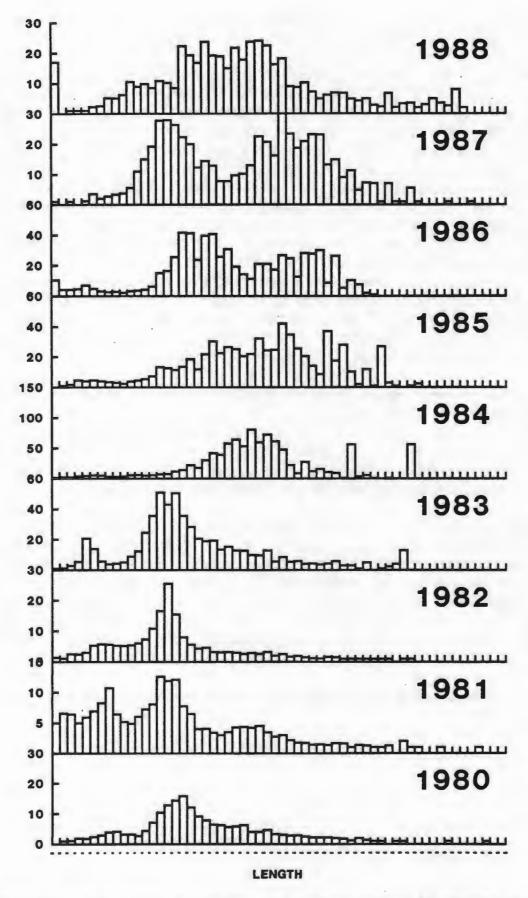


Figure 42 Length frequency histograms for northern anchovy in midwater nets of the Bay Study 1980-1988. Note elimination of small size class after 1983 and its gradual return.

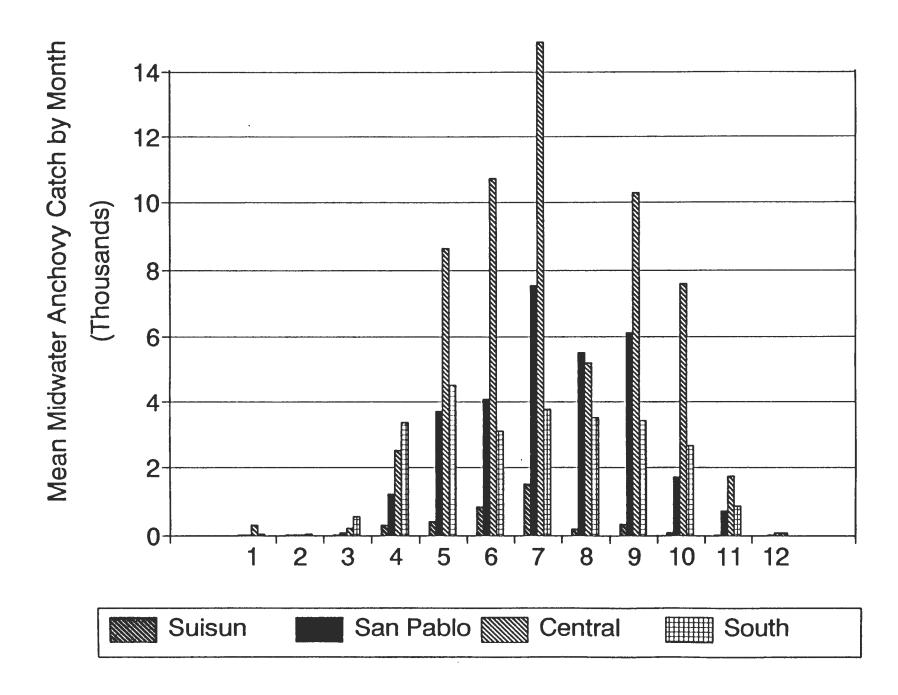


Figure 43 Mean catch per month of northern anchovy in midwater nets of the Bay Study 1980-1988.



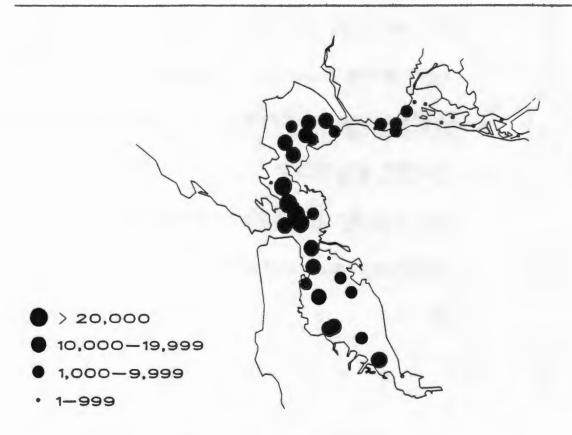


Figure 44 Distribution of northern anchovy in midwater nets of the Bay Study 1981-1984 vs 1985-1988.

Pacific herring support a large fishery in the Bay, particularly for roe which is exported to Japan. Adult and juvenile herring are caught and sold for bait and some are sold fresh or canned as human food but it has never been a large fishery. As much as 3,629 metric tons were landed for a reduction fishery in 1918, but this market was eliminated by the Reduction Act of 1919 (Spratt 1981). As with northern anchovy,

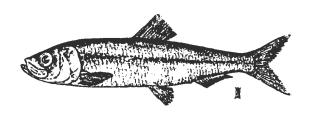


Figure 45 Pacific herring

an attempt was made in the 1940's and 1950's to substitute herring for the failing sardine fishery but the efforts met with little consumer acceptance. The roe fishery consists of two separate harvests (Spratt 1981). Divers collect eggs after they have been deposited on *Laminaria* or *Gracilaria*, to be sold in Japan as 'Kazunoko Kombu.' Spawning adults are caught mostly in gill nets in order to select the largest individuals and the ovaries of the ripe females are taken to be sold in Japan as Kazunoko). Gonadal weight in ripe herring approaches 22% of body weight (Hay and Fulton 1983). The roe fisheries began in 1972 and instigated the first scientific studies of herring in California (Spratt 1981).

Although herring appear to be very adaptable to changing conditions on the spawning grounds there is a need to identify what ecological features might explain the history of collapses that have characterized herring fisheries (Doubleday 1985). The Baltic Hanseatic League of the 16th century provides the earliest example of a collapsed herring fishery (Blaxter 1985). Recruitment appears to be the limiting stage on herring abundance (Doubleday 1985), so fisheries such as that for Kazunoko may be most likely to affect abundance. Herring are flexible and resilient so that, even where overfishing has destroyed a fishery, it may be possible to restore the population (Blaxter 1985; Ware 1985). In San Francisco Bay, where the population is still thriving, possibilities for effective management seem good if harvest rates stay below quotas or is a better understanding of the biology of the species permits the application of scientifically based quotas.

San Francisco and Tomales Bays attract the largest spawning aggregations of herring in California (Spratt 1976). Adults begin migrating into bays one to two months before actually spawning (Miller and Schmidtke 1956), in San Francisco Bay immigration begins in November and spawning generally occurs between December and February (Wilson 1937; Scofield 1952; Spratt 1981). The size of the spawning population has been relatively stable, with the largest variation associated with *El Niño* conditions of the 1976-1977 and 1983 (Table 8). The decline in biomass of 1976-77 was accompanied by greater than usual spawning biomasses in Tomales Bay. The decline in catch during 1983 was apparently part of a reduced oceanic population of herring in response to reduced productivity. Reasons for the general increase of herring abundance through time, despite increasing commercial catch, is unclear.

Table 8. Estimated spawning biomass of Pacific herring in San Francisco Bay. Data prior to 1980 from Spratt (1981), estimates after 1980 from personal communication with J. Spratt, CDF&G Marine Resources Division.

Spawning season	Estimated spawning biomass (thousands of metric tons)
1974-1975	27
1975-1976	25
1976-1977	22
1977-1978	4
1978-1979	33
1979-1980	46
1980-1981	65
1981-1982	99
1982-1983	59
1983-1984	41
1984-1985	47
1985-1986	49
1986-1987	57
1987-1988	69
1988-1989	66
1989-1990	71

Pacific herring spawn in a very restricted area of San Francisco Bay. Most of the spawning occurs in intertidal and shallow habitats of the Tiburon Peninsula and Angel Island, although some spawning occurs on aquatic vegetation near Berkeley and Richmond (Spratt 1981). Herring will not spawn over the mud substrates which characterize much of the shallow, intertidal habitat on the east side of the Bay. The apparent transferral of spawning to Tomales Bay for the 1977-78 season suggests that, despite the restricted spawning requirements and tendency for races to return to natal sites, herring will likely respond to habitat loss in the Bay by using other coastal sites.

American shad populations rapidly increased following their planting in 1871 (Love 1991). The semi-buoyant eggs probably reduced the impact of siltation on egg mortality and the use of river channels for spawning, rather than small tributary streams like salmonids, probably also gave them a much better chance to successfully spawn in spite of the effects of hydraulic mining. Eight years after planting, American shad supported a commercial fishery and rapidly

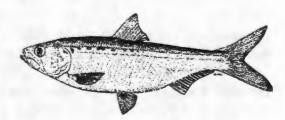


Figure 46 American shad (from Moyle 1976)

spread to all other estuaries from Alaska to Baja California. Their spread was facilitated by additional introductions into other estuaries, but their spread throughout the region and as far away as Kamchatka underscores the great degree to which this fish moves in the ocean. Maximum size of adult American shad is 760 mm and many of the spawning fish weigh 2 to 3 kg. Runs of American shad in the Sacramento River have been estimated at up to 4 million fish. American shad spawn for the first time at ages ranging from two to five years; about 70% of

the fish spawning in any year are first time spawners (R. Painter 1979, unpublished report, CDF&G).

American shad are oceanic as adults except for a brief spawning run in freshwater. Most central California adults spawn in the Sacramento River or its tributaries; spawning in the Delta or San Joaquin River accounts for little of the recruitment. Within their native range American shad seldom eat while on the spawning migration, but in the Sacramento-San Joaquin estuary they continue to feed as they pass through the Bay and generally cease feeding in freshwater (Moyle 1976). Most young American shad rapidly migrate downstream after hatching but a few can remain as long as a year. Many adults die after spawning but some return to the ocean and spawn again in later years.

The CDF&G sampling programs are ill suited for studies of American shad. By the time of the Fall Midwater trawl survey most young shad have already begun their migration out of the Delta. The significance of the place and timing of this is revealed in the fact that the greatest catch of American shad in the Fall Midwater trawl survey occurs in September and declines least rapidly in Suisun Bay (Table 9), the first sampling month and the most downstream location. The Bay Study does not sample in the Delta where American shad are most concentrated and where most mortality of young fish occurs. The peak catch in Bay Study trawls occurs in August or September of all years, which reinforces the suspected bias of the Fall Midwater Trawl survey. Catch of American shad in Suisun Marsh is very lo8w (Moyle et al. 1985). Midwater and otter trawls used in this study are poor sampling gear for larger fish. More than 99% of the American shad caught by the Bay Study were young of year (<170 mm total length). Lengths are not available for most years of the Fall Midwater Trawl survey, but the timing of the trawls almost ensures the absence of adults. No recent estimates of spawning numbers were found through contacts with biologists of CDF&G.

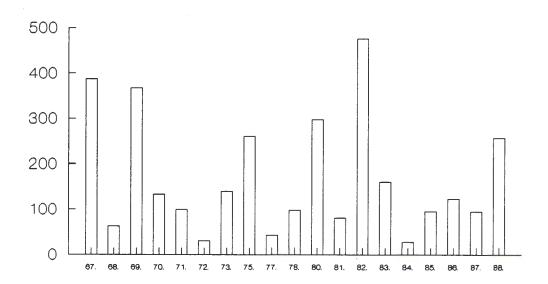


Figure 47. Catch of American shad in September trawls of the CDF&G Fall Midwater Trawl survey.

Despite these biases it is still possible to determine some patterns in the data. Stevens and Miller (1983) describe the apparent increase in American shad recruitment in wetter years.

Including more recent data confirms the earlier study. Lower catches of American shad have generally occurred during drought periods, 1976-77 and 1985-1988 (Figure 47). American shad captures in the Bay Study fluctuate during the first four years and are not lowest in 1981, although that was a dry year. The four lowest catches of American shad by the Bay Study occurred in the last four years, which were all dry (Table 10).

Table 9. Mean catch of American shad in fall midwater trawls. All trawls included.

	Sacramento	San Joaquin	Suisun Bay
September	6.6	13.8	7.22
October	4.7	7.56	5.99
November	4.9	5.17	5.42
December	2.4	1.92	2.54

Table 10. Catch of American shad in trawls of the CDF&G Bay Study.

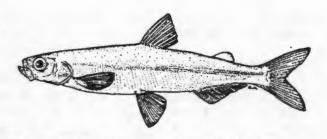
	80	81	82	83	84	85	86	87	88	Overall
January	18	28	7	22	5	13	5	16	7	121
February	16	42	3	12	5	17	10	7	2	113
March	13	14	1	2	2	6		2	2	42
April	2	13	2	1	6	1	2	4	3	34
May		13	11	1			1	4		30
June	3		6				2	1	1	13
July	3		86	6	121			1 5	31	258
August	41	30	506	79	60	18	14	21	63	832
September	14	59	220	281	40	20	36	26	13	709
October	44	92	205	84	23	25	63	18	24	578
November	23	36	172	51	14	16	17	8	17	354
December		7	48	23	10	15	15	11	12	141
Total for										
Year	183	334	1267	562	285	131	165	123	175	3225

The mechanism most likely to explain the linkage of American shad abundance with outflow is that temperatures over 20 C are known to produce high mortality in young shad. Drought conditions are often accompanied by increases of temperature in the smaller volume of water so that young shad are stressed. This effect is likely most effective within the Delta or upstream because temperatures recorded from Suisun Bay during the months of American shad abundance show no upward shift through time (Table 11).

Table 11. Mean temperatures (C) in Suisun Bay for each month and year of the Bay Study.

	80	81	82	83	84	85	86	87	88 mean
Jan	9.3	10.4	7.5	6.9	9.0	7.9	8.4	8.9	7.0 8.3
Feb	12.6	10.9	8.9	9.9	10.5	8.6	11.2	9.1	9.5 9.8
Mar	14.4	14.4	11.9	12.2	12.4	11.9	13.4	11.6	13.9 12.7
Apr	16.7	15.3	14.0	13.1	13.9	13.8	16.1	15.2	17.0 15.0
May	17.6	18.1	16.5	15.0	17.3	16.6	16.1	20.0	15.6 17.0
Jun	19.4	21.6	18.2	20.2	19.2	21.3	18.9	19.7	17.9 19.6
Jul	21.0	21.1	21.2	22.2	22.7	21.3	21.0	20.8	21.1 21.5
Aug	19.5	20.7	21.3	22.1	22.5	20.0	19.7	21.2	20.4 21.0
Sep	20.2	19.5	20.1	22.5	21.9	19.7	18.8	20.7	19.0 20.4
Oct	16.7	18.5	18.9	19.3	19.8	18.6	17.5	19.3	17.7 18.6
Nov	10.9	16.1	14.7	17.6	14.6	15.4	16.0	17.2	16.0 15.7
Dec	na	11.8	10.6	10.0	10.1	10.5	12.1	12.8	11.8 11.2
All	16.3	16.2	14.0	16.2	16.4	15.3	15.7	16.3	15.4 15.7

Delta smelt are confined to the upper Sacramento-San Joaquin estuary. They have been proposed for endangered status and the information here is condensed supporting documents for the petition (Miller et al. 1990; Moyle et al. 1991). Historically, the upstream limits of their range have been around Isleton on the Sacramento River and Figure 48 Delta smelt. (from Moyle 1976) Mossdale on the San Joaquin River, with the



lower limit being Suisun Bay (Radtke 1966; Moyle 1976; Lee Miller, CDF&G, reports catching Delta smelt above Sacramento). It seems likely that, prior to the reclamation of Delta islands, Delta smelt occurred much further upstream. Their small mouths and rather restricted diet on copepods suggest that Delta smelt feed by picking individual food items from the water column. When the Delta was more productive food may have been dense enough to allow Delta smelt to feed over a wider range; their present concentration in the mixing zone may simply mean that it is the only remaining area with dense enough populations of copepods to permit these fish to harvest enough to keep alive.

Prior to their sharp decline in abundance after 1984, Delta smelt concentrated in shallow water areas near the entrapment zone or in the river channels immediately above it, except when spawning. In Suisun Bay, 62% of the smelt were captured at three stations less than 4 m deep; 38% were captured at six stations greater than 4 m deep. The shallow depth preference of Delta smelt is most apparent when compared with longfin smelt which show a reverse pattern of distribution, arguing that catch at one depth is not simply a result of greater trawl efficiency in shallow water. Most smelt were also caught upstream of areas where there was a large difference between surface and bottom specific conductances or in the channels of the lower Sacramento and San Joaquin Rivers (Figure 50). They were rarely caught in similar areas in San Pablo Bay where the water was more saline than in upstream areas.

During times of exceptionally high outflow from the rivers, Delta smelt may be washed into San Pablo Bay but they do not establish permanent populations there (Ganssle 1966). Delta smelt inhabit surface and shoal waters of the main river channels and Suisun Bay where they feed on zooplankton. Stevens and Miller (1983), could not find any relationship between smelt abundance and outflow.

The mean monthly catches of Delta smelt in the Fall Midwater trawl survey vary from month to month and from year to year; an additional survey for juveniles in the Summer shows a very similar pattern (Figure 49). However, some trends are evident. From 1967 through 1975, fall catches were generally greater than 10 smelt per trawl per month (6 of 8 years); from 1976 through 1989 catches were generally less than 10 smelt per trawl per month (13 of 14 years). Since 1986, catches have averaged considerably less than 1 smelt per trawl per month. The Bay Study and Suisun Marsh study show sharp declines in Delta smelt at about the same time.

Overall, Delta smelt concentrated in or immediately upstream of the entrapment zone. Comparing the overall patterns of stratification in Suisun Bay for the period prior through 1984 to data from the same stations after 1984 shows a general difference in location of the entrapment zone. In the earlier period the entrapment zone was located in Suisun Bay during October through March except during months with exceptionally high outflows or during years

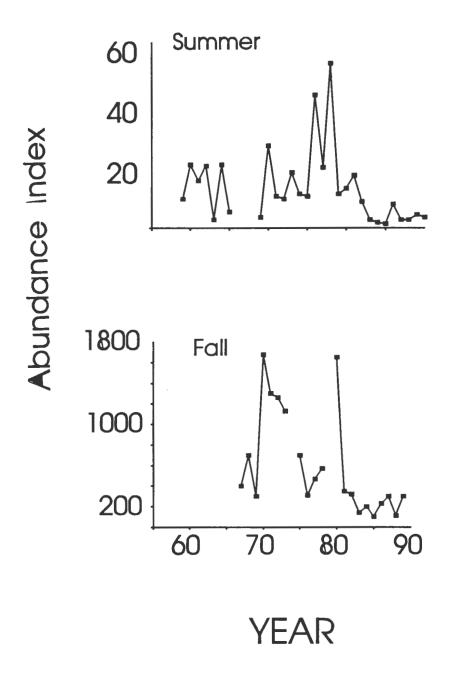


Figure 49. Index of abundance for Delta smelt from the Summer Townet Survey and Fall Midwater Trawl Survey.

of extreme drought. During April through September they were found usually upstream, in the channels of the rivers. Since 1984 the entrapment zone, just upstream of the stratified water column, has been located mainly in the channels of the rivers during all months of the year (Figure 50). In Figure 50 the heights of the bars indicate the overall average difference in salinity measured at the the surface and at the bottom; this difference indicates stratification and the upstream limit of stratification indicates the position of the mixing zone. The line indicates mean catch per trawl at each station. Notice that in the later 4 years the mixing zone is generally upstream of its location in the first four years and that Delta smelt have moved accordingly moved upstream. This shift in the location of the entrapment zone during the winter

months coincides with an upstream shift and narrowing of the location of the Delta smelt population to the deeper water of the main river channels (Figure 51).

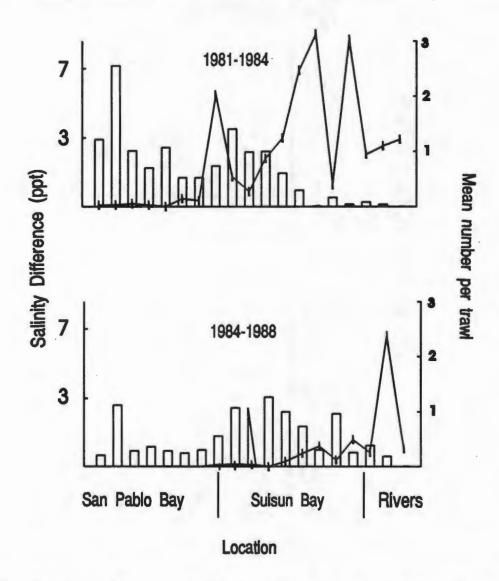
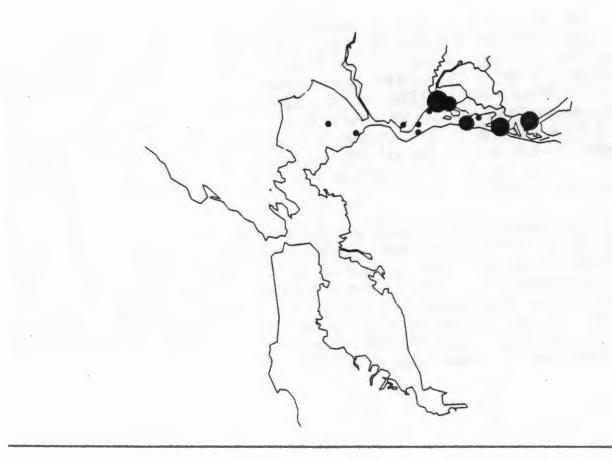


Figure 50. Salinity stratification and abundance of Delta smelt at Suisun Bay stations the period from May to October. Bars give difference in conductivity between surface and bottom, line gives mean Delta smelt capture.

The frequency of occurrence of Delta smelt in the trawls has also declined. Prior to 1983, Delta smelt were found in 30% or more of the fall trawl catches. In 1983-85, they occurred in less than 30% of the catches, and from 1986 onwards they have been caught in less than 10% of the trawls. The trend of a dramatic decline in Delta smelt numbers after 1982 is also reflected in the total catch data, although sampling efforts have been higher since 1980. This trend is reflected as well in the annual catch data from two other studies for which effort was more or less constant. The exact timing of the decline is different in most of the sampling programs but falls between 1982 and 1985. Length-frequency data validates earlier studies, showing that the Delta smelt is primarily an annual species, although a few individuals may survive a second year.

Captures of larval Delta smelt indicate that spawning can take place in fresh water any time from late February through May, when water temperatures are from 7 to 15°C (Wang 1986), although most spawning occurs in March and April. Spawning occurs in shallow water along the edges of the rivers and adjoining sloughs (Radtke 1966, Wang 1986) but spawning behavior has not been observed. Delta smelt embryos are demersal and adhesive, sticking to hard substrates such as rocks, gravel, and tree roots (Moyle 1976, Wang 1986). Hatching occurs in 12-14 days, if development rates of the embryos are similar to those of the closely related wagasaki, *H. nipponensis* (Wales 1962).



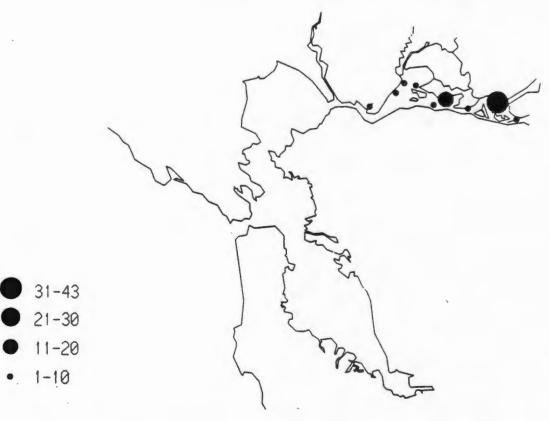


Figure 51 Map of delta smelt distribution in the period from May to October for the two time periods 1980-1984 and 1985-1988.

After hatching, the buoyant larvae are carried by currents downstream into the entrapment zone of the estuary where incoming saltwater mixes with outflowing fresh water. The mixing currents keep the larvae circulating with the abundant zooplankton that also occur in this zone. Growth is rapid and the juvenile fish are 40-50 mm fork length (FL) by early August (Erkkila et al. 1950, Ganssle 1966, Radtke 1966). Delta smelt become mature when 55 to 70 mm FL and rarely grow larger than 80 mm FL. Delta smelt larger than 50 mm FL become increasingly rare in samples in March through June, so presumably most adults die after spawning, completing their life cycle in one year (Erkkila et al. 1950, Radtke 1966).

The fall midwater trawl data census only the adults but since the bulk of the population, if not the entirety, lives only one year this accurately reflects total recruitment from the previous season's spawning.

Four major factors were examined in relation to smelt distribution and abundance: electrical conductivity (specific conductance), temperature, depth, and freshwater outflow. Conductivity was regarded as particularly important because it is a measure of salinity that is highly correlated with other variables such as turbidity and productivity and was used to track the mixing (entrapment) zone. At each sampling station, specific conductance (and salinity) and temperature were measured with a salinity-conductivity-temperature meter at the surface. To determine the location of the mixing (entrapment) zone, we used specific conductance data collected monthly since January 1981 by the Bay Study, in which both surface and bottom specific conductance's were measured. The large difference between the two measurements indicated the presence of stratification, as incoming fresh water is less dense than tidal salt water. A small difference in specific conductance indicated a well-mixed water column or stations located entirely in fresh water.

Movement of the entrapment zone into Delta channels is a result of low Delta outflow, which is calculated primarily from the sum of Delta inflows minus the water diverted and used within the Delta. Since 1983, the proportion of the water diverted during October through March (first half of the official water year) has been higher than in most earlier years. Because high levels of diversion draw Sacramento River water across the Delta and into the channel of the San Joaquin river downstream of the pumps, the lower San Joaquin River has a net flow upstream during these periods (Figure 52; actual instantaneous flow in the channels is a function of outflow and tidal action). The number of days of net reverse flow of the San Joaquin River has consequently increased in recent years, especially during the months when Delta smelt are spawning (Figure 53). The decline in Delta smelt coincides with the increase in proportion of water diverted since 1983 and the confining of the entrapment zone to a small area in the channels of the lower rivers. Other major changes in estuarine conditions (increased toxic loads, explosive spread of other species) did not happen at the same time as the decline of Delta smelt and are therefore less likely to have been the cause. Determination of causality, however, cannot be done without experimental manipulation of diversion schedules.

The Delta smelt is a species that is best suited for living in the entrapment zone of the Sacramento-San Joaquin estuary where it feeds on the concentrations of copepods and other zooplankton there. When the entrapment zone is located in Suisun Bay, optimal conditions for smelt occupy a much larger total area that includes extensive shoal areas than they do when the entrapment zone is located in the Delta upstream. The river channels in the Delta are comparatively small in surface area and have few shoal areas, so are less favorable to the Delta

smelt. Because the Delta smelt is essentially an annual fish with relatively low fecundity, a large entrapment zone with extensive shallow areas immediately downstream from its spawning areas must have been a predictable part of its environment during much of the smelt's evolutionary history. Increasing diversions of fresh water from the estuary have altered the location of the entrapment zone, as well as the flow patterns of the Delta during most months of the year. The movement of the entrapment zone to the river channels not only decreases the amount of area that can be occupied by smelt but probably results in decreased phytoplankton and zooplankton as well (Herbold and Moyle 1989; Appendix A). During the months when Delta smelt are spawning, the changed flow patterns presumably draw their larvae from the Sacramento River into the San Joaquin River, where they can be exported through the pumps along with locally produced larvae.

This problem has no doubt been exacerbated by the near-drought conditions that have existed in the drainage since 1987, coupled with the record high outflows that occurred in February, 1986 (which may have flushed fish out of the estuary). However, since 1984 the percentage of inflow diverted has been higher and stayed higher for longer periods of time than during any previous period, including the severe 1976-77 drought.

Although the recent high diversions of fresh water coupled with drought conditions are the most likely cause of the precipitous decline in the Delta smelt population, other factors that may be contributing are (1) toxic compounds in the water, (2) displacement of native copepods by exotic species, and (3) invasion of the estuary by the euryhaline clam, *Potamocorbula amurensis*. Pesticides in the Sacramento River at concentrations potentially harmful to larval fish and zooplankton have been recorded in recent years by the Central Valley Regional Water Quality Control Board (C. Foe, personal communication). The effects of these pesticides on smelt is unknown, but they have occurred at high levels in fresh water prior to the most recent decline of the smelt. The concentration of smelt in the mixing zone may have allowed them to avoid the effects of pesticides, because of the dilution of the contaminated fresh water by inflowing seawater.

Increases in the abundance of two exotic copepod species have been associated with a reduction in the abundance of *Eurytemora affinis*, principal food of the Delta smelt. The invasion of *Sinocalanus doerri* occurred prior to the smelt decline, although the invasion of *Pseudodiaptomus forbesi* apparently occurred around 1986. Although *S. doerri* is apparently rarely eaten by Delta smelt, *P. forbesi* is now a major part of their diet. Meng and Orsi (1919) have found that larval striped bass readily take *P. forbesi* but have a difficult time capturing *S. doerri*. Despite this, it does not appear that the shift in copepod species has had a major impact on Delta smelt populations because the smelt have shifted their diet as well.

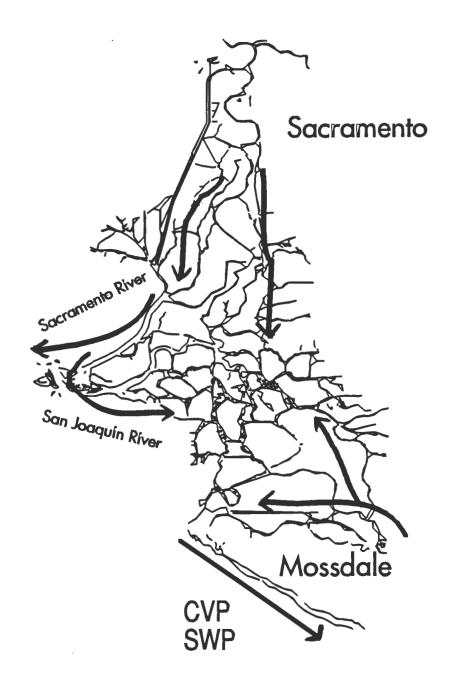


Figure 52 Map showing pattern of reverse flow in lower San Joaquin which formerly characterized summertime conditions but which has predominated at all times of year since 1985.

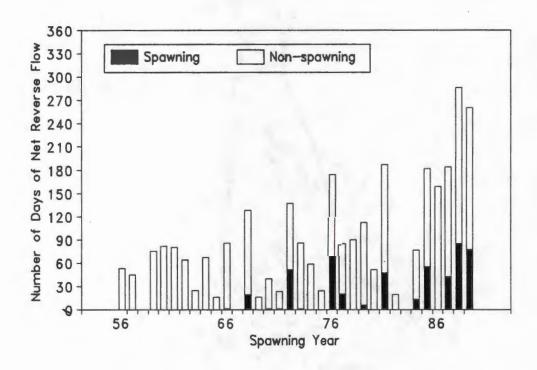


Figure 53. Number of days in each year when net flow was reversed in lower San Joaquin River. Time of Delta smelt spawning indicated as solid bar.

Longfin smelt (Spirinchus thaleichthys) are small planktivores found in several Pacific coast estuaries from Prince William Sound, Alaska to San Francisco Bay. Until 1963 the population in San Francisco Bay was thought to be a distinct species, the Sacramento smelt. Northern populations were originally described as a different species (S. dilatus, Schultz and Chapman

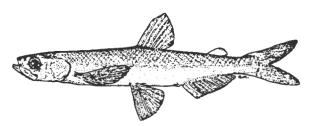


Figure 54 Longfin smelt. (from Moyle 1976)

1934) but the identifying characteristics were shown to follow a gradient and the two species were merged (McAllister 1963). Although studies in other estuaries are scanty, it appears likely that the population in San Francisco Bay has been the largest population. Within California, longfin smelt have been reported from Humboldt Bay and the mouth of the Eel River but there are no recent records from the Eel and it is infrequently collected in Humboldt Bay (R. Frizsche, pers. comm.).

Longfin smelt differ substantially from Delta smelt. Consistently, a measurable portion of the longfin smelt population survives into a second year. The larger mouth of the longfin smelt reflects the greater proportion of large zooplankton in their diet - particularly the mysid shrimp *Neomysis mercedis* (Moyle 1976; Wang 1986; Herbold 1988). Adult longfin smelt are broadly distributed throughout the estuary.

Because longfin smelt seldom occur in freshwater except to spawn but are widely dispersed in brackish waters of the Bay, it seems likely that their range formerly extended as far up into the Delta as salt water intruded. Prior to construction of Shasta Dam, salt water would invade the Delta as far upstream as Sacramento during dry months. Similarly, Delta smelt appear to require denser concentrations of zooplankton than the hydrology of the Delta now permits. Thus, the development of agriculture and water projects probably restricted the ranges of both species before any studies of their biology were begun.

The primary ecological similarity between the two smelt species is their use of the river channels at the easternmost end of the San Francisco Bay complex for spawning. In both species the adhesive eggs hatch after a few days and currents normally transport the larvae downstream. If changes of flow in the spawning ground is the mechanism by which Delta smelt have suffered decimation, then we expected the same pattern to appear in longfin smelt.

Although longfin smelt populations were known to be affected by freshwater inflow to the estuary (Stevens and Miller 1983), there has been little concern for their persistence in the estuary as they have been regarded as abundant and widely distributed, with additional populations in other California estuaries (Moyle 1976, Monaco et al. 1990). A recent compilation of fish species of special concern for California, for example, does not list them (Moyle et al. 1989).

As reported from the general descriptions of their biology (Moyle 1976; McGinnis 1985; Wang 1986), longfin smelt in the records of CDF&G are more broadly distributed in the Bay. They are found at higher salinities than Delta smelt. The easternmost catch of longfin smelt in the Fall Midwater trawl was at Medford Island in the Central Delta. They have been caught at all stations of the Bay Study. A pronounced difference between the two species in their region

of overlap in Suisun Bay is by depth; longfin smelt are caught more abundantly at deep stations (>10 m) whereas Delta smelt are more abundant at shallow stations (<3 m).

In both South Bay and Central Bay, a brief dominance by longfin smelt occurs in the midwater catch in 1983. In San Pablo and Suisun Bay their abundance in 1983 was lower than their abundance in 1982, thus supporting the idea of washout from upstream.

Unlike Delta smelt, longfin smelt have a measurable portion of their population survive into a second year. In addition, there is a significant difference in the distribution of longfin smelt of different sizes. After hatching, young longfin smelt are most abundant in the otter trawls of San Pablo Bay and larger fish are generally caught in midwater trawls in Suisun Bay. This difference is most pronounced immediately after spawning but the difference in size for each month for the two nets is significant for all but one month of the year (Figure 55). Whereas longfin smelt are segregated from Delta smelt in Suisun Bay by their use of deeper stations and greater occurrence in the otter trawl, in San Pablo Bay they occur more commonly in the midwater trawl. Comparing the catch of each net through time in each embayment shows that longfin smelt have nearly disappeared from San Pablo Bay and from the otter trawl (Figures 56 and 57). A procedural shift in the minimum size at which longfin smelt were included in the catch causes the catches to not be strictly comparable across years; the data presented in figures 56 and 57 are only for those fish that were greater than 40 mm in length, all fish of this size were counted in all years.

Longfin smelt populations in the 1980's have followed a trajectory similar to that shown by Delta smelt. Abundance was high in 1980, low in 1981, high again in 1982, and in sharp, continuous decline from 1983 through 1988. The decline in 1981, a dry year for which Delta smelt remained at relatively high numbers, reflects their dependence on high outflows described by Stevens and Miller (1983). Longfin smelt failed to recover in 1986, nominally a wet year, because record flows in February presumably flushed a high percentage of mature adults out of the Estuary.

Unlike Delta smelt, which declined in frequency of occurrence but not in abundance at the stations at which they are still caught, longfin smelt have retained most of their earlier distribution but their catch at each station has declined (Figure 58).

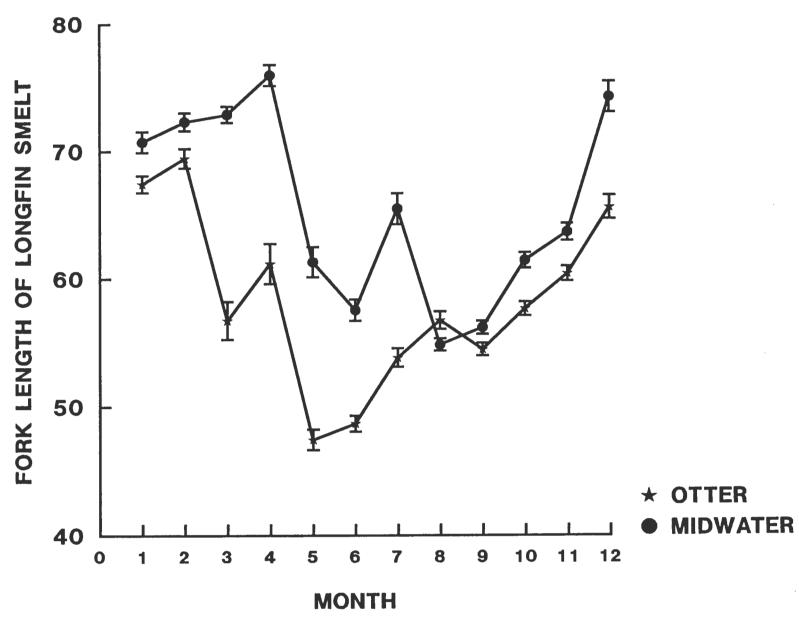


Figure 55 Differential capture of longfin smelts of different sizes in the midwater and otter trawls of the Bay Study.

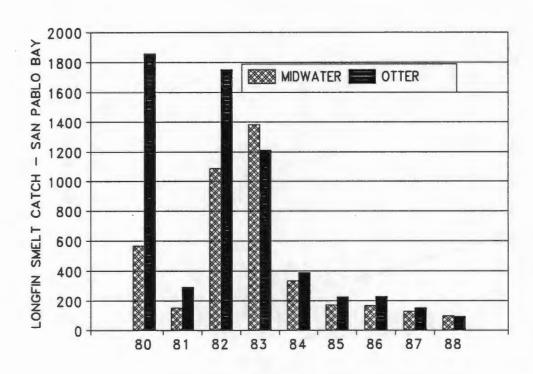


Figure 56 Decline of catch of longfin smelt (> 40 mm fork length) in the midwater and otter trawls in San Pablo Bay (data from CDF&G Bay Study).

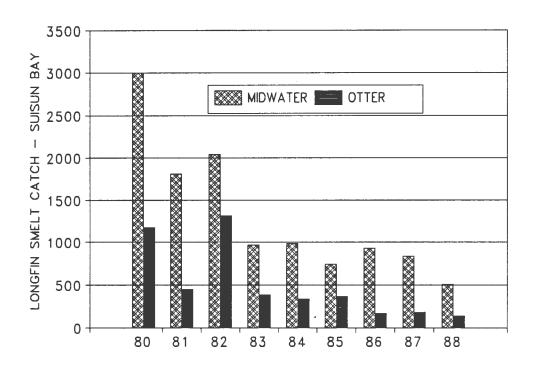
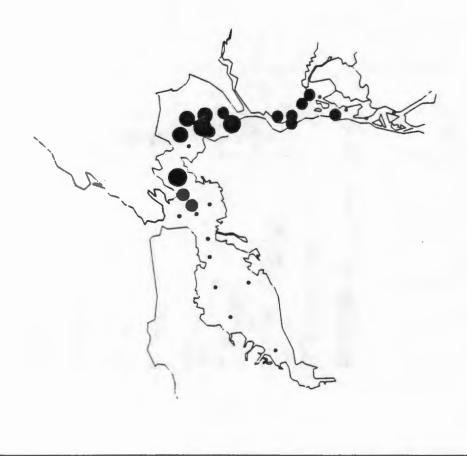


Figure 57 Decline of catch of longfin smelt (>40 mm fork length) in the midwater and otter trawls in Suisun Bay (data from CDF&G Bay Study.)



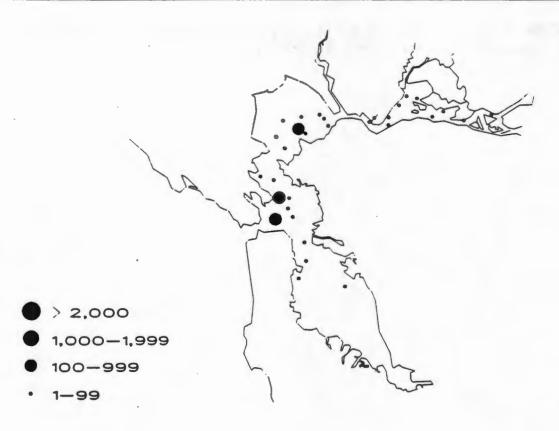


Figure 58 Distribution and abundance of longfin smelt at each of the consistent sampling sites of the Bay study.

Threadfin shad (Dorosoma petenense) were introduced from Tennessee into the Sacramento-San Joaquin river system in 1953 to provide a forage base for largemouth bass in reservoirs (Burns 1966). Downstream spread introduced the species into the Delta where it is abundant. Threadfin shad are a relatively minor component of striped bass diet (Moyle 1976). Shad usually occur in more-or-less even aged schools, with schools of young frequently living in deeper, more open-water habitats than adults (Johnson

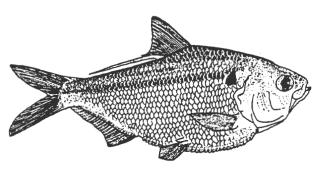


Figure 59 Threadfin shad. (from Moyle 1976)

1970). Feeding appears to be relatively non-selective on planktonic crustacea (Turner 1966, Miller 1967). Threadfin shad seldom exceed 100 mm total length.

The extremely long and fine gill rakers collect a wide variety of plankters and the presence of a thick-walled muscular crop permits digestion of all kinds of zooplankton.

Threadfin shad spawn in the late spring and on through the summer (Johnson 1971; Moyle 1976). The demersal and adhesive eggs are often laid on drifting or partially submerged objects. Cold temperatures are presumed to be the cause of annual die-offs of large numbers of shad in the waters of the Delta (Turner 1966a).

Threadfin shad are found usually east of Sherman Island, except during times of high outflow. Their catch in Bay Study trawls was remarkably constant and low (Table 12) for all years except 1983, which can be attributed to washout from upstream since that was the wettest year on record in California. Most of the catch occurred during the wet season of each year and, as the drought progressed through the last years of the study, threadfin shad were increasingly restricted to the wetter months.

Table 12. Sum of catch of threadfin shad in Bay Study hauls. Both nets and all stations combined. Forty-two percent of the catch was made in the midwater trawl at the four easternmost stations.

	MONTH												
		1	2 .	3	4	6	7	8	9	10	11	12	TOTAL
	80 81 82	1	2	1		2	2	5	9	31	1 3 7	29 8	44 34 36
Y	83 84	23 13	5 9	-	3	1		4	89 1	41 15	29 13	41 12	233 66
A R	85 86	1	10	2						3 14	3 1	18 18	37 36
	87 88	14 22	2 6	1				1			1	26 9	44 38
	TOTAL	86	34	4	3	3	2	10	99	108	58	161	568

In the Fall Midwater Trawl surveys threadfin shad were the most abundant species of fish caught in the Delta for all but five years since the study began in 1967 (Table 13). The portion of the population of threadfin shad inhabiting the Sacramento River waters appears to be subject to somewhat different processes than those shad living in San Joaquin River waters.

Table 13. Abundance of five most abundant species in Delta in the catch of the Fall Midwater Trawl Survey. All stations east of Chipp's Island included.

Year	Striped Bass	Shad American	Smelt Threadfin Del		TAL gfin	FISH
67	2033	1423	8579	141	410	13014
68	2336	318	3403	429	127	6898
69	1097	1325	5161	62	177	8142
70	711	182	1428	122	10	2625
71	407	236	2120	252	44	3265
72	482	57	1913	136	11	2644
73	283	131	441	70	9	1358
75	281	419	326	48	22	1177
76	123	40	295	82	30	606
77	861	159	3717	468	162	5620
78	752	725	740	101	270	3041
80	645	1489	2865	594	1413	7069
81	754	302	2752	49	277	4220
82	402	1246	976	41	140	2834
83	180	447	526	1	13	1189
84	468	95	302	36	319	1280
85	397	310	448	68	307	1623
86	1741	592	1326	83	535	4443
87	663	341	1757	227	390	3541
88	205	789	1081	87	204	2411
TOTAL	14821	10626	40156	3097	4870	77000

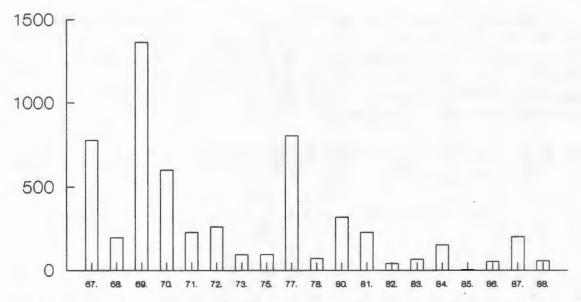


Figure 60. Catch of threadfin shad in September at stations consistently sampled by the Fall Midwater Trawl survey.

The greatest number of shad have been captured in San Joaquin River waters. Examining several representative years shows the spatial and temporal distribution of the species. In September almost all the shad are concentrated at the stations furthest upstream. After the onset

of the rainy season shad begin to be captured at stations further downstream, so that by December threadfin shad are at their lowest numbers and greatest distribution. Die-offs of threadfin shad are a frequent occurrence in the lower estuary as temperatures drop to below the shads' lower tolerance level. Across years there is a declining trend of threadfin shad abundance at most stations, primarily due to exceptionally high catches in the first few years of the study which have not been seen since (Figure 60).

Embedded within the general decline in abundance are differences in the rate of decline at different stations. Four stations in the area with the greatest number of threadfin shad were sampled in September of all years. In October the water year begins and shad densities decline sharply at all stations as the shad are transported downstream. Data from these stations were analyzed to look for patterns in the association between the abundance of threadfin shad and the location of the station in the path of cross-Delta flows.

Two of these stations (910 and 912) are in the San Joaquin River near Stockton and receive only San Joaquin river water. The other two stations (906 and 908) are in the path of flow from the cross-Delta channel. All stations show a significant correlation with year. Diversion rates also increased across years so that a correlation with diversion is inevitable. In order to determine if being in the path of cross-Delta flow is tied to rapidity of shad decline, we examined partial correlations remaining after removing the effects of the correlation in both variables with year. Both stations in the path of diverted water showed highly significant partial correlations between September shad abundance with the quantity of water diverted during the preceding six months. The two stations upstream showed no significant partial correlations.

In the Sacramento River threadfin shad are much less abundant but they are more evenly dispersed than in the San Joaquin. Stations closer to the central Delta generally support the largest catches of threadfin shad. After the start of winter rains they are quickly displaced.

Adult threadfin shad are most abundant in the dead-end sloughs of the Delta and, so, are usually less susceptible to capture by the Fall Midwater Trawl series than are young-of-year. Data on fish lengths from this dataset are only available for the three years 1986-1988, however average lengths decreased significantly for each successive year of this period. This shrinkage of mean size is most likely the result of decreasing washout of adults from the dead-end sloughs because these three years were the beginning of a long period of little rainfall. Thus, more of the catch was probably younger fish coming from upstream populations and fewer from adults residing in the Delta. The effect of washout on the number of fish captured in the midwater trawls is shown by the downstream spread of threadfin shad over the course of the four months of the fall midwater trawl surveys.

### 6.7.5 Conclusions about planktivores

Expected trends for San Francisco Bay populations of northern anchovy and Pacific herring in the face of projected changes to the Bay include a continued dominance of the fish community by northern anchovy. This species is not limited to spawning only in the Bay and is not limited to any particular habitat in the Bay. Pacific herring appear potentially more sensitive to the effects of global warming. Increasing severity and frequency of winter storms may directly interfere with successful spawns by erosion of shallow habitats that support the algae they spawn upon, and by forcing conversion of these habitats into breakwaters and dikes to protect low-lying property.

American shad are probably the anadromous species best able to survive the continuation of present conditions or of most foreseeable changes in estuarine habitat. Both adults and juveniles pass through the estuary rapidly. By spawning in tributary rivers, American shad do not face the loss of spawning habitat that salmon have suffered. Their ability to spawn repeatedly also allows the population to survive years when spawning conditions are poor. They are also out of reach of entrainment by water diversions in the Delta that are the most likely cause of declines in the smelt and striped bass. The larger size of adult American shad makes them less susceptible to displacement by changes in flow patterns than either of the smelts or of threadfin shad.

Threadfin shad appear to be ill-suited to the present flow regime in the Delta because they are easily entrained and difficult to screen. However, upstream populations are large and can be expected to continue to provide large numbers of individuals to populate the Delta.

Deepening of channels across the Delta and decreased transit times of water will serve to increase the displacement or entrainment of threadfin shad. Flooding Delta islands as a consequence of rising sea levels might provide the sorts of reservoir-like habitats where threadfin shad populations in the state have thrived. However, the islands most likely to be lost are those of the western Delta where threadfin shad are less abundant and which would probably be unsuitably salty for threadfin shad to use year-round. Alternative water transport plans are likely to most seriously affect the upstream reaches of the Delta and so amplify their current effects on threadfin shad.

The two smelt species do not overlap greatly in geography, habitat, or diet but they do spawn in the same area. It is clear that their parallel declines in abundance is most likely due to the changes in their spawning habitat. The recent switch to conditions of net reverse flow in their spawning grounds for most of their spawning seasons, which coincides with their rapid declines, provides a simple and sufficient explanation for their present plight. The dissimilarity of response to the dry year 1981 suggests that dry years, by themselves are insufficient to threaten the survival of the species.

Both smelts are likely to continue to suffer loss of young due to their requirement of breeding within the Delta, which will probably continue to be an inhospitable place during low flow years for any fish with planktonic larvae. Levee failures, however, could provide a major increase in suitable habitats for feeding and maturation of Delta smelt. This species is likely to have been much more broadly distributed in the Delta prior to diking, dredging, and water diversion because more of the water would have probably supported zooplankton densities sufficient to support young smelt. The present restriction to the entrapment zone makes them more susceptible to displacement and entrainment than longfin smelt but water storage on islands in the western Delta, or levee failures, might provide habitats similar to the original Delta in which they evolved.

#### 6.7.6 Piscivores

While a lot of research and discussion have surrounded the biology of striped bass in the estuary, almost nothing has been written on the biology of the probably the most abundant native piscivore in the Bay, white croaker (*Genyonemus lineatus*). White croaker eat a wide variety of foods including a number of small fish species. Although they generally live and feed near the bottom they have been observed chasing schools of northern anchovy at the surface (Love 1991). A partial explanation for the difference in intensity of scientific study is reflected in the attitudes of many Caucasian anglers who have a variety of unpalatable names for white croaker (e.g. 'sewer trout' Love 1991). However, they are avidly sought and eaten by anglers and shoppers of several ethnic minorities and they are extremely abundant in the middens of coastal Indians of California (Love 1991).

White croaker, or kingfish, are similar to striped bass in several important respects. White croaker mature in 2-3 years and can live for up to 15 years (Frey 1971). Striped bass males mature in 1-3 years, the females mature in 2-4 years and can live up to 30 years (Raney 1952, 1954; Moyle 1976). Striped bass spawn April through June in the rivers and white croaker spawn from November to May, mostly in the Gulf of the Farralones. Eggs are non-adhesive and pelagic. In both species and currents play an important role in the distribution of larvae: river currents carry the newly hatched striped bass downstream to Suisun Bay and concentrate them in the mixing zone, bottom currents carry newly hatched croaker into the Bay and they congregate in shallow areas. Fish of both species may move to the ocean as they mature but all life stages occur in the estuary.

Significant ecological differences also distinguish the two species: Striped bass spawn above or in the upper reaches of the estuary whereas white croaker spawn in the Gulf of the Farallones or in the lower reaches of the estuary. White croaker are primarily bottom fishes from the time they hatch and are quite omnivorous, but striped bass are dependent on neritic food at all stages of their life. Striped bass are much more euryhaline than croaker and, so, occur much more abundantly in the freshwater parts of the estuary.

The white croaker population in San Francisco Bay uses the Bay in three different ways, depending on age. (Figure 62). Eggs are broadcast around April in the Central Bay or outside the Golden Gate and are carried by tidal currents into upstream parts of the Bay (Wang 1986). Young of year greater than 15mm FL usually begin to be collected by the Bay-Delta study in May (Figure 63a). At about the same time juveniles from the preceding year's spawning re-enter the bay and concentrate in the deeper stations of

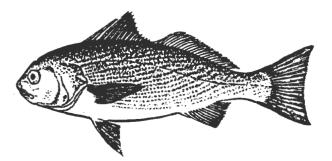


Figure 61 White croaker. (modified from Eschmeyer et al. 1983)

South Bay (Figure 63b). The deeper stations of South Bay also support a year-round population of older fish (Figure 63c). In October or November the young of year and juveniles migrate out of the Bay. In recent years more adults have moved into shallow areas of San Pablo Bay during the spawning season, perhaps as a response to increasing salinity due to drought conditions. Thus, all three life stages migrate into the Bay but movements are in response to different conditions and are largely independent of each other.

Abundance of young-of-year white croaker shows little evidence of trends across the nine years of data. Catches in 1980, 1986 and 1988 were all at very similar high levels; more than twice that of most other years. These years of high catches do not appear to share any distinguishing features in their weather patterns. The abundance of young of year is uncorrelated with the abundance of juveniles in the following year or with the abundance of older fish two years following.

White croaker have changed in abundance, distribution, and age distribution in San Francisco Bay since the start of the Bay Study. Juvenile and adult croaker abundances in the Bay are both tightly correlated with the passage of time (Spearman's rho for both = .97, p<.01). Adult croaker in the last years of the study were found more frequently in the shallow stations at the spawning season. Young of year white croaker are predominately found in the shoals of San Pablo Bay. The increasing use of the Bay as a spawning site probably explains the greater abundance of young of year in 1986 and 1988. Rank abundance of young of year is significantly correlated with the rank abundance of adults present in that year (Spearman's rho = .67; p=.05).

Distribution of white croaker within the Bay presents a confused picture (Figure 64) because of the differing shifts shown by different age classes. Because fewer young appear to have entered the Bay in the recent years of low outflow, the abundance of young in San Pablo Bay has declined. However, the larger, more resident population of mature white croaker are spawning within the Bay so that young present in the Bay in recent years arise from an entirely separate process than the young caught in the earlier years.

Overall, it appears that the abundance of young in the Bay increases in response to greater immigration during high outflow years or in years when adults spawn in the Bay. However, in either case, the migration of young out of the Bay mixes them with a larger population in the ocean so that higher spawning in the Bay does not lead to higher catches in later years of juveniles or adults in the Bay.

White croaker appear likely to continue their spread of juveniles and adults into parts of the Bay previously only used by young-of-year, as salinities in those areas decline in variability. Increased water diversion rates in the face of increasing frequency of drought conditions and rising sea levels will both tend to stabilize salinities in San Pablo Bay, probably favoring fish like adult white croaker which have been common in South Bay. Increased spawning within the Bay and decreased wintertime flows out of the Bay are likely to broaden the seasons when white croaker occur.

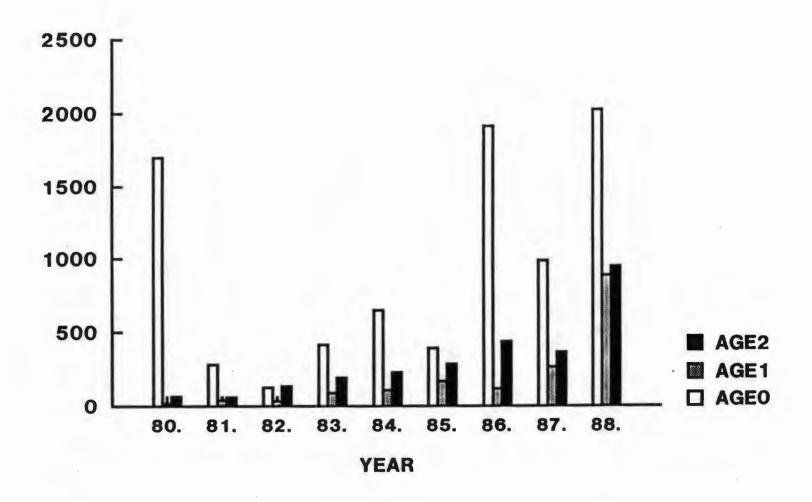


Figure 62 Presence of different life stages in San Francisco Bay through time of white croaker, from catches by the Bay study.

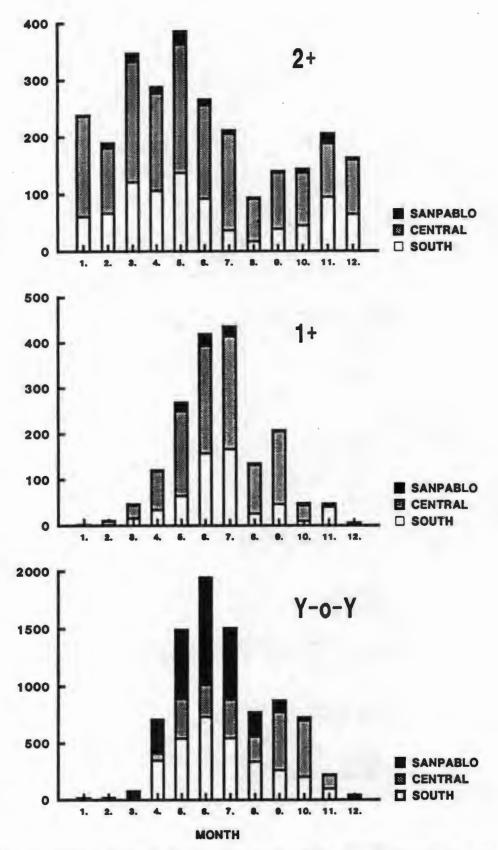


Figure 63 Abundance of three age classes of white croaker from otter trawls of the Bay study: the bottom is the catch of young of year, in the middle is of year old juveniles, at the top is data for two year old and older.



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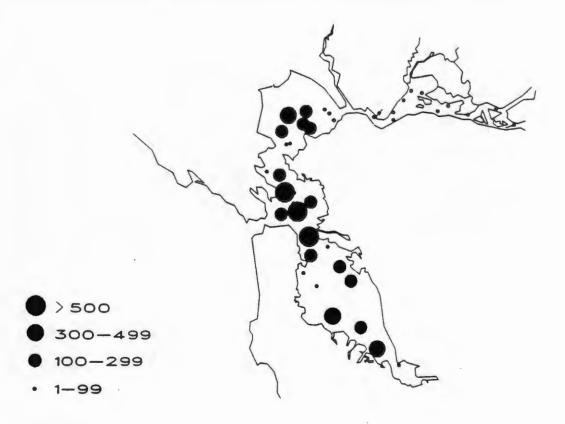


Figure 64 Distribution of all ages of white croaker for the first and second halves of the period of sampling by the Bay study

# 6.7.6.1 Flatfish

English sole and starry flounder are very similar bottom-foraging flatfish that spawn outside the Golden Gate and rely on landward flowing bottom currents to carry their prolarvae into the Bay (Wang 1986). Starry flounder penetrate much further into the Bay than English sole and can be found in the estuary throughout the year whereas English sole are markedly seasonal in occurrence (CDF&G 1987).

English sole occur in the Bay predominantly as young of year. Adults support a commercial ocean fishery but do not enter the bay in significant numbers. Spawning occurs in shallow areas all along the coast from November to May (Wang 1986). Newly released eggs

are buoyant but they lose buoyancy immediately before hatching. However, newly hatched larvae are found at the surface. (Budd 1940). Larvae remain pelagic for 6 to 10 weeks (Herrgesell et al. 1983; Wang 1986). As the larvae transform, at a length of about 15-20 mm, they descend the water column and many are transported by density-driven bottom currents into the Bay. The importance of San Francisco Bay as a nursery ground for the coastal population of English sole is unclear.

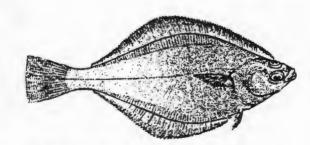


Figure 65 English sole (from Hart 1973)

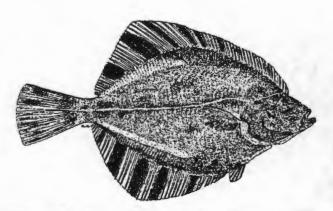


Figure 66 Starry flounder (from Eschmeyer et al. 1983)

Starry flounder occur in San Francisco Bay in high numbers for all life stages. A substantial ocean population supports a small commercial fishery (Frey 1971), and adults in the Bay support a popular sport fishery. Early descriptions found larvae in the lower San Joaquin River and supposed that they were the products of adults spawning there and in Suisun Bay (Radtke 1966). Later investigations have suggested that spawning takes place at the mouths of estuaries and bottom currents move the larvae inland (Wang 1986).

English sole and starry flounder both use bottom currents to transport their young into the Bay, but it appears that the Bay is more important as a nursery ground for starry flounder because their spawning adults appear more likely to migrate into the reach of bottom currents (Gunter 1942; Orcutt 1950).

English sole are more abundant than starry flounder in the catches of the Bay study, partly due to a much larger percentage of young of year. The English sole population in the Bay study otter trawls is almost exclusively young of year. New young of year appear in January, while the previous year's young are still present. By May the previous year's young, (120-180)

mm FL) have left the estuary and only the current season's young (20-100 mm FL) remain. They appear to greatly slow their growth in October.

Examination of length frequency histograms shows that starry flounder maintain at least three age classes throughout the year in both San Pablo and Suisun Bays. The high abundance of young of year can temporarily mask the abundance of older fish in June-August, but by December the older fish comprise about half the catch. The smallest starry flounders are found further upstream in Suisun Bay from May to October. By November the modal size of young is the same in both bays. It seems most likely that the larger larvae settle out of the bottom currents earlier than the smaller ones so that the young ones are transported further inland.

As with most other similar species in the estuary, the two abundant flounders have different centers of distribution (Figure 67). English sole are primarily in Central Bay and spill almost equally into South and San Pablo Bays. Starry flounder are most abundant, and most diverse in sizes, in San Pablo Bay but many young are found in Suisun Bay.

English sole have varied in catch at the Bay Study stations from a low of 417 in 1987 to a high of 2315 in 1984, but they show little evidence of a trend through time (Figure 68). English sole are most variable in their catch in San Pablo Bay; the highest catch in San Pablo Bay occurred in 1988 and constituted 60% of the total catch but in 1983 San Pablo Bay accounted for only 5% of the catch.

Starry flounder show a pronounced trend through time (Figure 69). A sharp decline is apparent in the starry flounder catch since 1983 and the last four years of the study are the four years of lowest flounder abundance. The decline has been sharpest in San Pablo Bay, which from 1985 to 1988 yielded less than 10% of the starry flounder captured at the same stations in 1980 to 1984, The decline in Suisun Bay is slightly less precipitous. The decline principally reflects a reduced production of young (Figure 70). The concentrations of toxic PCBs in adult starry flounder have been shown to be sufficient to reduce reproductive success (Spies et al. 1988; Spies et al. 1990; Davis et al. 1991).

Examination of the spatial distribution of starry flounder emphasizes the two areas of concentration within the Bay (Figure 71). Near Alcatraz, the catch has declined but is still geographically isolated from the catch in San Pablo Bay. The population in San Pablo Bay has drastically declined and there is a corresponding decline in the number of young found in Suisun Bay. There appear to be two populations, an offshore one whose young appear near the mouth of the bay and a resident one which appears to breed and stay year-round in the northern reaches of the Bay. Obviously each population is susceptible to different limiting factors.

Several anomalous features arise in comparing the two flatfish species. Both are presumed to rely on bottom currents for the transport of their newly settling larvae. However, the English sole shows little or no evidence of decline in abundance in the Bay, despite the fact that almost all English sole in the Bay are young of year. Low outflows should draw fewer young fish upstream in both species, but only starry flounder have declined. In fact, English sole have spread further upstream in the recent drought years and the largest catch (still only 10 fish) of English sole in Suisun Bay occurred in 1988. On the other hand, starry flounder are more likely to spawn in the Bay and should be less responsive to lowered outflows. Just the opposite has actually occurred; starry flounder have many fewer young in the Bay in recent years and they have declined more markedly in San Pablo Bay than in Suisun Bay despite the decreased force of bottom currents. Curiously, in 1988, while English sole were occurring more

frequently upstream, starry flounder were found in their second greatest abundance in South Bay.

The small effect of weaker bottom currents on English sole immigration and the less steep decline of starry flounder in Suisun Bay suggest some extrinsic factor, such as toxic contamination in the sediments, may be involved in the decline of starry flounder in San Pablo Bay. Organic contaminants in San Pablo Bay are sufficient to reduce the reproductive success of starry flounder (Speiss et al. 1989, 1990).

The two flatfish species offer strong contrasts in expected trends in response to changing climatic conditions and benthic communities. The resident population of starry flounder appears to share the fates of striped bass, Delta smelt and longfin smelt due to its dependence on hydrologic and other environmental conditions of San Pablo and Suisun Bay. The future of starry flounders in the Bay appears to be that they will cease to maintain a separate inland population and will, like the English sole, only use the Bay for a brief period as a nursery area for young of year. The decline of the San Pablo Bay starry flounder population coincides with increased presence of English sole. This may reflect biotic interactions or simply greater dispersion due to increasing abundance of English sole young entering the bay. Bottom-dwelling habits, feeding on the benthos, and wide salinity tolerances may allow young flatfish of both species to continue using the Bay despite most projected changes in physical conditions.

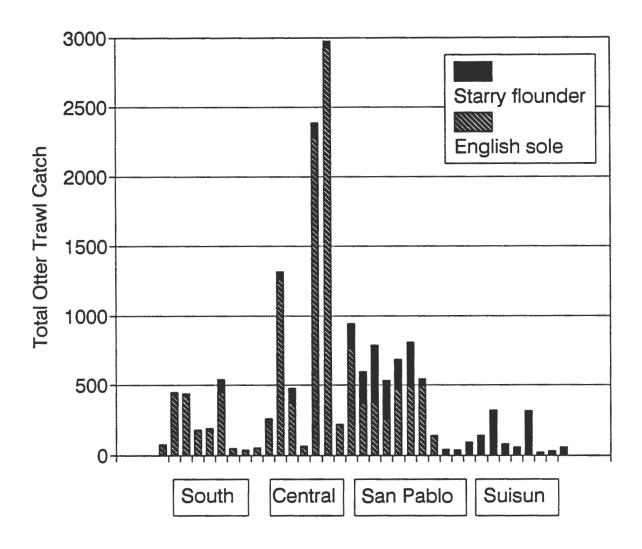


Figure 67 Distribution of abundance of English sole and starry flounder in otter trawls of the Bay study

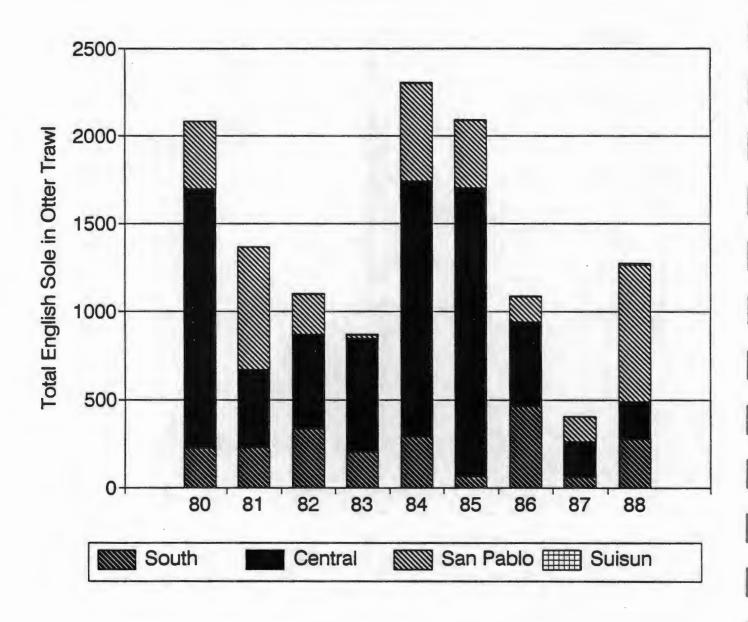


Figure 68 Catch of English sole through time, 1980-1988 (data from otter trawls of the Bay Study.

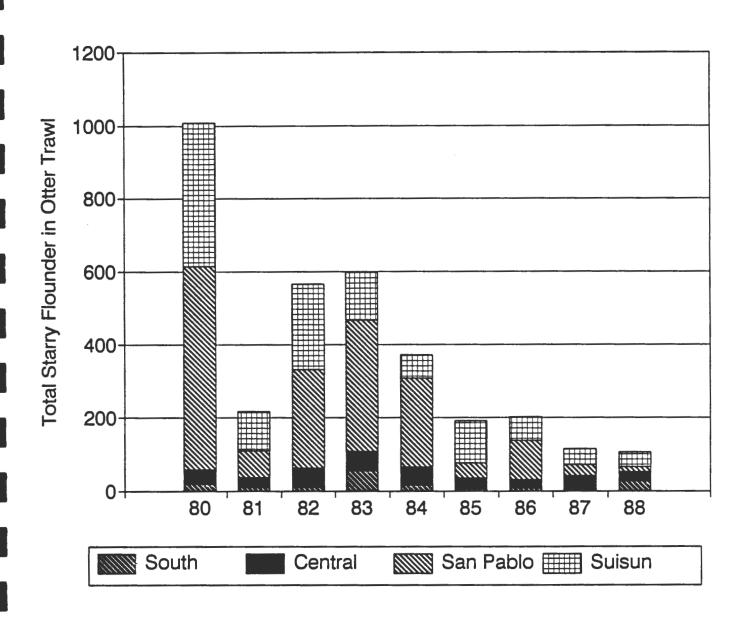


Figure 69 Catch of starry flounder through time, 1980-1988 (Data from otter trawls of the Bay Study)

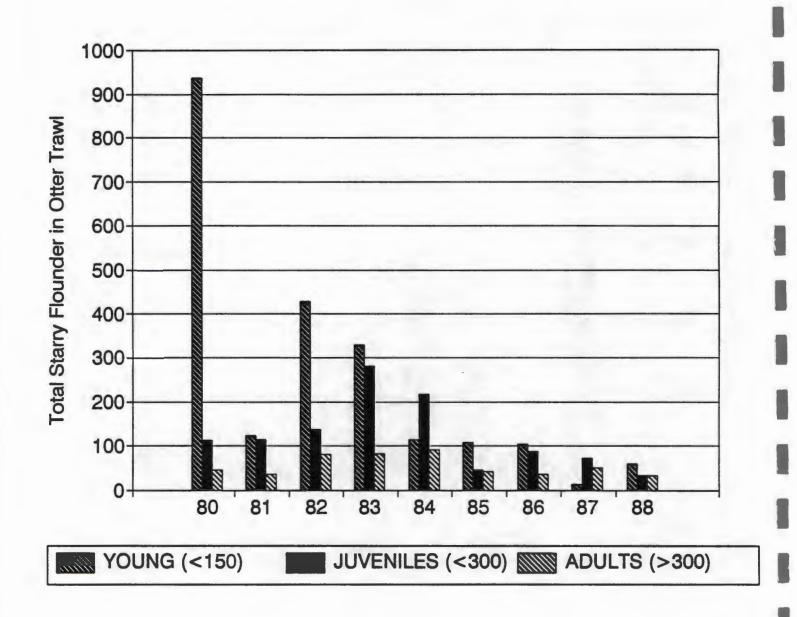


Figure 70 Trends across years of three age classes of starry flounder.



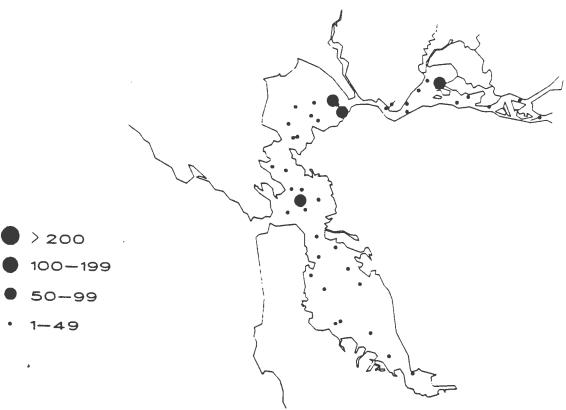


Figure 71 Comparison of distribution of starry flounder between 1980-1984 vs 1985-1988.

# 6.7.6.2 Surfperches

Nineteen species of surfperch (family Embiotocidae) occur in California's waters and thirteen of them have been collected by the Bay Study. These fish are small livebearers; the largest species seldom exceeds 18 inches and most are mature at only six to seven inches (Miller and Lea 1972; Eschmeyer et al. 1983). As their common name implies they are most frequently found

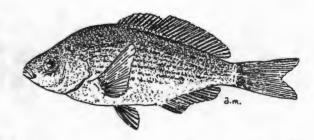


Figure 72 Shiner perch. (from Moyle 1976)

in the surf zone, both over sandy beaches and in rocky areas. Studies of their behavior in kelp forests and rocky reefs show that they are usually rather sedentary, with the same individual often being found in one area for long periods of time (Hixon 1980; Ebeling et al. 1983). All species give birth to fully developed young which immediately begin feeding in the same habitat and manner as the parent. Most species are primarily found in marine habitats but the shiner perch (Cymatogaster aggregata) is usually found in bays, and is more than ten times as abundant as any other member of the family in the catches of the Bay Study. California is the only home of the only freshwater member of the family, the tule perch (Hysterocarpus traski). Tule perch are patchily distributed throughout the Sacramento Valley, with a large population in Suisun Marsh. Because they feed among emergent vegetation, tule perch are not captured often by either the Bay Study of the Fall Midwater trawl survey. However the sampling program in Suisun Marsh of University of California at Davis collects them frequently. The species which occur in the Bay, but have most of their populations along the coast, may be transported into the Bay by bottom currents since they are bottom feeders that do not appear to travel great distances. However, some species have been shown to migrate in response to changes in ocean temperature or toward warm water from power plant discharges (Allen et al. 1970; Terry and Stevens 1976; Hose et al. 1983). The species in the Bay include black surfperch (Embiotoca jacksoni), white surfperch (Phanerodon furcatus), pile perch (Rhacochilus vacca), dwarf surfperch (Micrometrus minimus), and barred surfperch (Amphistichus argenteus).

Because they are live-bearers, surfperch reproduction is not apt to be affected by the sorts of changes in habitat or food abundance that are likely to affect the larvae of most other fish.

The surfperches of San Francisco Bay can be placed into three groups:

- 1) the freshwater tule perch,
- 2) the shiner perch which is characteristic of the Bay below Carquinez Strait, and
- 3) marine species. These three groups show two patterns of abundance through time in the Bay. The marine species have all declined in the catch of the Bay Study since the mid-1980s. Prior to 1985 the species show few similarities in patterns of abundance (Figure 73). However, all species fell to lower levels in the period 1983-84, and since then the less abundant species have remained an lower abundances. This cannot be entirely ascribed to weaker bottom currents because there is no consistent pattern in any of the species with earlier patterns of outflow.

Tule perch and shiner perch, although they show very little overlap in geographical distribution show very similar trends in abundance through time (Figure 74 and Figure 75). Both species declined in 1983, a year of extremely high outflow, and gradually recovered over the following four years. The decline in shiner perch is greatest in San Pablo Bay and least in

South Bay. The mechanism producing this decline is unclear but the timing and area of greatest effect indicate that the very high outflow of this year is involved. Perhaps some other aspect of *El Niño*, which produced the high outflow, might be responsible for the decline, but the more marine surfperch show no apparent change in abundance from 1982 to 1983.

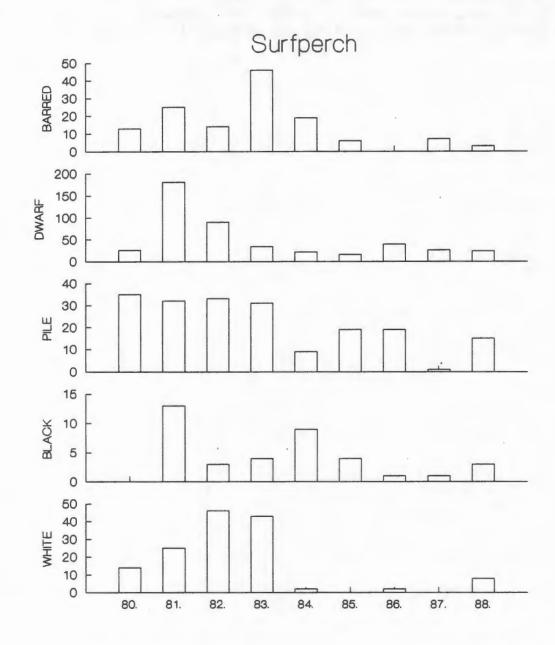


Figure 73. Catch of five marine species of surfperches through time from data of the Bay Study.

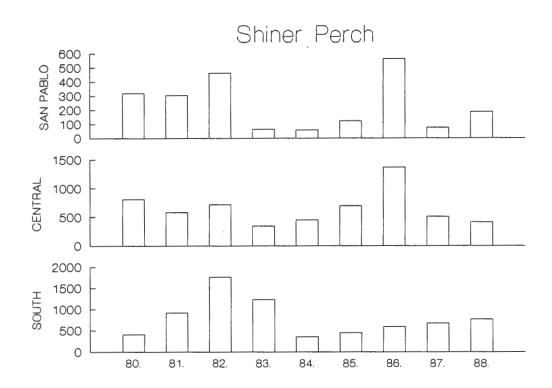


Figure 74. Catch across years of shiner perch in otter trawls of the Bay Study in each of the lower embayments.

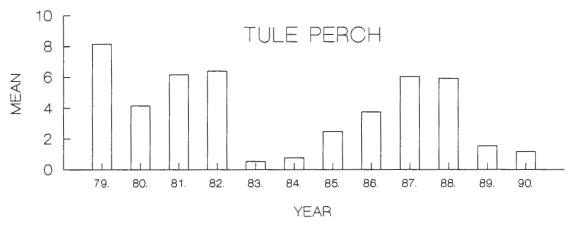


Figure 75. Catch per trawl of tule perch in otter trawls performed in Suisun Marsh by UCD personnel.

### 6.7.6.3 Other native freshwater fishes

Data is largely lacking on the trends in the abundances of other native freshwater fishes in the Estuary, but some general comments are nevertheless possible. Sacramento squawfish (Ptychocheilus grandis), Sacramento sucker (Catostomus occidentalis), and Sacramento blackfish

(Orthodon microlepidotus) are still fairly common. Squawfish and sucker are most abundant in the western Delta where water quality is highest, but can be found throughout the upper estuary, while blackfish are largely confined to dead-end sloughs (Turner and Kelley 1966; CDFG, unpublished data). Hitch (Lavinia exilicauda) are also characteristic of dead-end sloughs but they are generally less abundant and more scattered in their distribution than blackfish; their status in the Delta is uncertain.

Sacramento splittail (Pogonichthys macrolepidotus) were once found throughout the Central Valley but are now confined to the Estuary (Moyle 1976). Their reproductive success is positively correlated with outflow (Daniels and Moyle 1983). In Suisun Marsh, they have declined steadily in abundance since 1979 (Moyle et al. 1985; Herbold and Moyle, unpublished data), a trend which is probably characteristic of its populations in the entire estuary. Thicktail chub (Gila crassicauda) and Sacramento perch (Archoplites interruptus) are now extinct in the Estuary (the chub is globally extinct) although both species were formerly abundant enough to be heavily utilized by local Native Americans (Schulz and Simons 1973). Sacramento perch were also harvested commercially in the 19th Century (Skinner 1962). The last thicktail chub was collected in the Delta in 1957 but the Sacramento perch is abundant in alkaline reservoirs and lakes into which it has been introduced, outside its native range.

### 6.8 Analysis of status and trends within groups of fishes

Most research on Bay fishes has focussed on identifying how species respond to outflow. Many of the studies on striped bass have explored the hydraulic mechanisms by which moderate outflows lead to the best larval survival in striped bass (Kelly and Turner 1966; Stevens 1977; Chadwick et al. 1977; Stevens 1979; Stevens et al. 1985). Stevens and Miller (1983) identified chinook salmon, American shad, and longfin smelt as 'wet year' species that increase in abundance in wet years. Moyle and Daniels (1983) showed that Sacramento splittail reproduce more successfully in wetter years and tied this, at least partly, to that species' need for flooded vegetation on which to lay their eggs. The Bay Study (Armor and Herrgesell 1985; CDF&G 1987) identified several species of fishes in the Bay characteristic of dry and wet years (Table 14). Pearson (1989), studying fish of the South Bay over some of the same years and earlier, identified a somewhat different collection of species characteristic of wet and dry years (Table 14). Pearson suggested that the discrepancies were due to the limited geographic nature of his study and the less intensive nature of the Bay Study.

Table 14. Species abundance responses to increased Delta outflows into south San Francisco Bay (after Pearson 1989)

Species	Pearson	CDF&G
Northern Anchovy English sole Shiner surfperch	Positive n Positive	Mixed response Mixed response Mixed response
Goby family Staghorn sculpin Pacific herring White croaker	Positive Negative	Positive Slightly positive Slightly positive Mixed response
Starry flounder	Slightly positive	Positive

We examined the grouping of species in the Bay Study and Fall Midwater Trawl datasets graphically and with principal components analysis. The graphs clearly indicate general changes in the catch in each embayment for each year. The principal components indicate which species covary across years, independent of their relative abundances. Because of the log-normal distribution of species within most communities the graphs of abundance generally show only the changes in the most abundant species. Such graphs are useful here because species composition has changed drastically through time for some embayments while remaining relatively constant in others.

#### 6.8.1 Graphic Analysis

Graphing the abundant species in the midwater trawl for each embayment, and excluding anchovy, produces a clear picture of trends across the nine years. These figures present the total catch for each species in each year. Interannual variability is extremely high for most species. Anchovy are excluded from these graphs because their abundance seems to be tied more to oceanic conditions and they seem to be very mobile within the Bay so that their abundance in one area does not accurately reflect their patterns of abundance in the Bay overall.

### 6.8.1.1 South Bay

In South Bay there has been a general increase in abundance of several species, particularly white croaker and plainfin midshipmen (Figures 76 and 77). The correlation of white croaker with the passing of time is the only significant association of any abundant species of South Bay (r=.90; p<.01). Jacksmelt and topsmelt are found in most Pacific coast estuaries (Moyle 1976; Wang 1986) and have long been recognized as characteristic fishes of South Bay (Ganselle 1966; Baxter 1966; Aplin 1967). Jacksmelt and shiner perch have been the least variable species. Topsmelt have particularly blossomed in abundance in two of the dry years, but show little consistency in abundance from year to year. In the early years of the decade Pacific herring were more variable in their abundance and the drought conditions seem to have promoted a stabilization in numbers at a level intermediate to that shown earlier. Although it rises and falls, the total catch in South Bay has increased but without much change in species composition. An exception is the brief domination of the catch by longfin smelt in 1983, apparently due to simple washout from upstream in that exceptionally wet year.

The otter trawl catch in South Bay shows weak patterns among the abundant species. White croaker show elevated abundances in the last three years but earlier years show wide variability. Bay goby show a similar pattern of consistently high abundance from 1986 to 1988 but earlier years attained similar abundances in some years. As in the midwater trawl, the onset of the drought coincides with a more consistent catch of shiner perch, but in the otter trawl the catch now is at a lower level than in most preceding years. English sole show a contrary pattern of much greater variability in later years. Bay goby and speckled sanddab show almost identical patterns of apparent multi-year cycles of abundance. Staghorn sculpins appear to vary widely but with more consistency from year to year than other widely varying species, steadily increasing to ten times their abundance from 1981 to 1985 and then steadily declining.

Overall, there is little overall change in the composition or abundance of the South Bay fish fauna, except increasing abundance of white croaker.

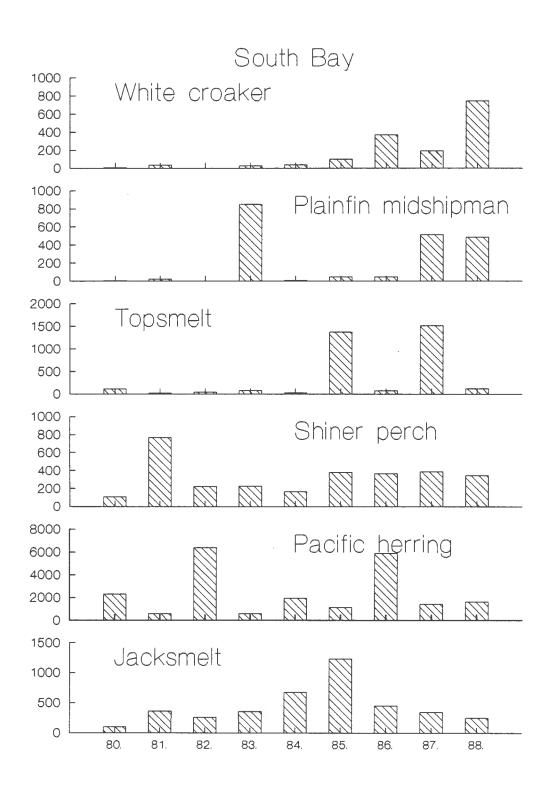


Figure 76 Catches of six dominant species of South Bay in midwater trawls across years (Northern anchovy excluded).

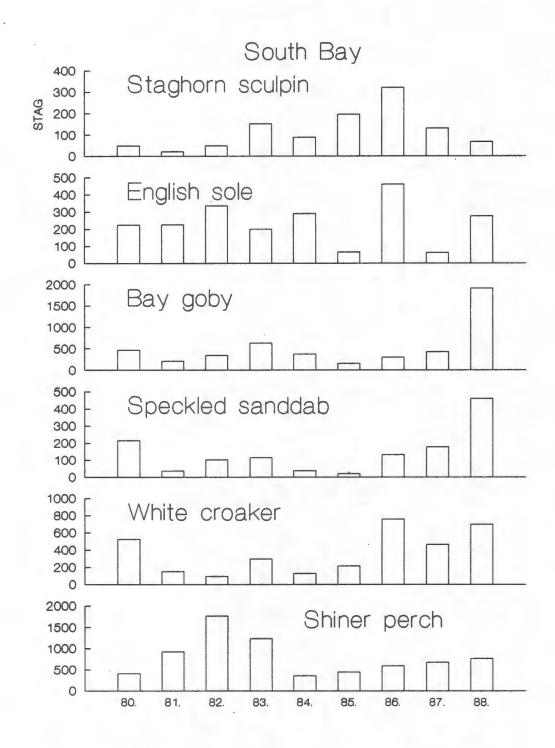


Figure 77. Catches of six most frequently captured species of South Bay in otter trawls of the Bay study through time. Northern anchovy excluded.

### 6.8.1.2 Central Bay

In Central Bay the midwater catch is quite variable, with no species sharing any pattern of abundance through time (Figure 78). As in South Bay, white croaker shows a strong increase in abundance (r=.90; p<.01). Shiner perch again are the least varying element of the catch, as they were in South Bay midwater trawls. Longfin smelt showed peaks in abundance in 1980 and 1983 which are much higher than any catch since 1984, but abundances were also very low in 1981 and 1982. Pacific herring and jacksmelt vary widely, and seemingly unpredictably, from year to year.

The otter trawl catch in Central Bay reflects several clear trends among the abundant species (Figure 79), a surprisingly result considering the presumed movements of many species through Central Bay. The changes in abundance from year to year are smaller than found in any other embayment. The steady rise and decline of staghorn sculpins that was seen in South Bay is exceptionally smooth in Central Bay. The increasing catch of white croaker in South Bay occurs in Central Bay as well (r=.83; p<.01), and seems to be a steady change unaffected by high outflows of 1983 and 1986. Longfin smelt show an almost equally smooth decline in catch across years, without the sharp peaks shown in the midwater trawl (r=-.68; p<.05). The rise and fall of bay goby, English sole and shiner perch populations do not appear to be in synchrony with major environmental variables or with each other.

Overall, there are few trends across time except for the decreasing abundances of longfin smelt and the increasing abundance of white croaker.

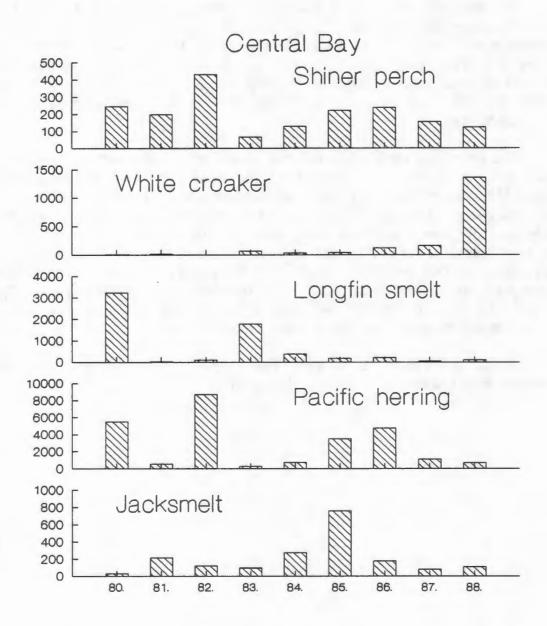


Figure 78. Catches of five most abundant species of Central Bay in midwater trawls of the Bay study through time (Northern anchovy excluded).

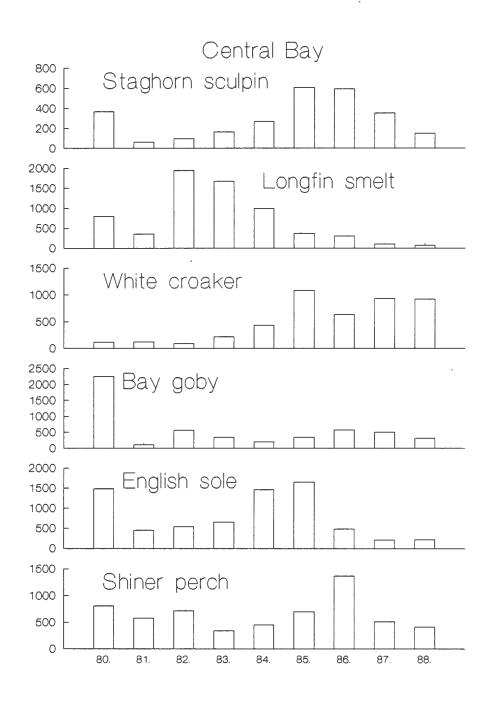


Figure 79 Catches of the six most frequently captured fishes in Central Bay in the otter trawls of the Bay Study (northern anchovy excluded).

# 6.8.1.3 San Pablo Bay

The midwater trawl catch from San Pablo Bay is highly variable and shows no patterns common among species (Figure 80). The decline of longfin smelt is the only obvious trend (r=.67; p<.05).

In the otter trawl (Figure 81), the characteristic species of San Pablo Bay, longfin smelt and starry flounder, share a significant pattern of decline (for longfin smelt r=-.85, p<.01; for starry flounder r=-.78, p<.05). Both species show similar responses to wet and dry years in the first half of the decade. Longfin smelt, starry flounder, striped bass, and staghorn sculpin all show positive responses to years of higher outflow (Spearman's r=.80, .82, .83, and .68, respectively). Anomalously low catches characterize most species in 1985.

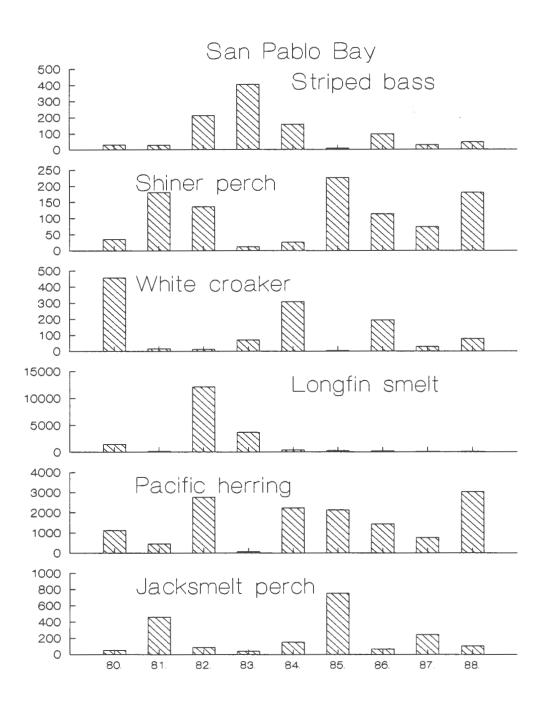


Figure 80. Catches of six most abundant species of San Pablo Bay in midwater trawls of the Bay study through time (northern anchovy excluded).

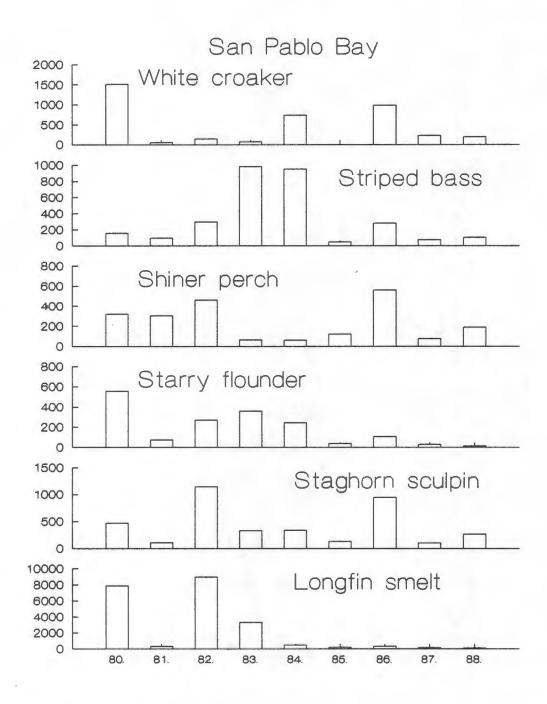


Figure 81. Catches of six most abundant species of San Pablo Bay in otter trawls of the Bay study through time (northern anchovy excluded).

### 6.8.1.4 **Suisun Bay**

Two patterns are shown in the midwater catch for Suisun Bay (Figure 82). Striped bass and American shad show their greatest abundance in 1982 and decline to record lows in the last four years of the study; the correlation with year, however, is not significant. Delta smelt and longfin smelt differ from American shad and striped bass in that they had high abundances throughout 1980-1983 and show a sharp decrease in abundance in later years. The correlation of abundance for these two species with passing years is significant (longfin smelt r = -.80, p < .05; Delta smelt r = -.85, p < .01). Pacific herring are extremely variable in abundance in Suisun Bay with no association with outflow or year, although the very high outflow of 1983 apparently prevented herring from entering Suisun Bay.

The otter trawl catch in Suisun Bay is similar to that of San Pablo Bay (Figure 83). Starry flounder and longfin smelt show significant declines through time (starry flounder r=-.87, p<.01; longfin smelt r=-.88, p<.01). The abundance of striped bass is similar to that in the midwater trawl, differing in the absence of the small peak shown in the midwater trawl in 1986. White sturgeon show a similar pattern from 1982 onwards, but with very small catches in the first two years of the study. Staghorn sculpin fluctuate over a wide range in the first four years of the study but seem to have stabilized at high levels in the last five years. Yellowfin goby vary widely from year to year.

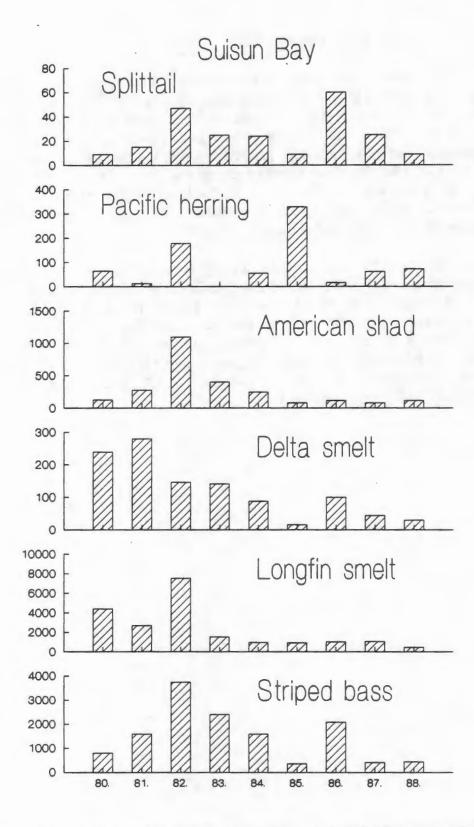


Figure 82. Catches of six most abundant species of Suisun Bay in midwater trawls of the Bay study through time (northern anchovy excluded).